Reliability Equivalents of AC Adequacy Evaluation of Large Power Systems

by

Atif Nazir Cheema

A Thesis Presented to the

FACULTY OF THE COLLEGE OF GRADUATE STUDIES

KING FAHD UNIVERSITY OF PETROLEUM & MINERALS

DHAHRAN, SAUDI ARABIA

In Partial Fulfillment of the
Requirements for the Degree of

MASTER OF SCIENCE

In

ELECTRICAL ENGINEERING

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COLLEGE OF GRADUATE STUDIES

Dedicated to

my mother

father, and brothers

Acknowledgment

In the name of ALLAH, Most Gracious, Most Merciful. Read in the name of thy Lord and Cherisher, Who created. Created man from a {*leech-like*} clot. Read and thy Lord is Most Bountiful. HE Who taught {the use of} the pen. Taught man that which he knew not. Nay, but man doth transgress all bounds. In that he looketh upon himself as self-sufficient. Verily, to thy Lord is the return {of all}.

(The Holy Quran, Surah 96)

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Abstract

Name: **Atif Nazir Cheema**

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The concept of utilizing the equivalents in the evaluation of large power systems, where sensitivity studies are to be done or the impact of the further interconnected system is to be examined, is a very powerful tool. The object of this thesis is to develop an adequacy equivalent model of a power system or part of it. The adequacy equivalent will utilize the a.c. load flow method for the sensitivity analysis of a composite power system. The execution time required for the adequacy analysis of composite power system will be reduced significantly using the concept of equivalent.

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خلاصة الرسالة

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لقد تم استخدام مفهوم المكافئات او النظائر لتقيم اداء الانظمة القوى الكهربائية و ذلك بدراسة حساسية الانظمة القوى الكهربائية، و تاثيرات ربط شبكات القوى الكهربائية، وقد اثبتت الانجات العلمية مقالية هذا المفهوم للتحليل الانظمة الكهربائية. هذة الرسالة تهدف ام تطوير نظام مكافئى و ملائم لنظام القوى الكهربائية او لجـز منة. و هـذا النظـام مبنـى علـى استخدام أسلوب تدفق أحمال التيار المتردد لتحليل حساسية انظـة القوى الكهربائية المركبة. ان نتائج هذا البحث تتحلص فى نقيل الوقت المستحدم فى اجرأ الحسابات

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Chapter 1

Introduction

A power system serves one function only and that is to supply customers, both large and small, with electrical energy as economical and as reliable as possible at the best quality possible. Modern society, because of its pattern of social and working habits has come to expect the power supply to be continuously available on demand. This is not physically possible in reality due to random system failures which are generally outside the control of power system engineers. The probability of the customers being disconnected can be reduced by increasing investment in resources during either planning phase, operating phase or both. Over-investment can lead to excessive operating costs which must be reflected in the energy tarrif structure. Consequently, the economic constraints may be violated even though the system may be very reliable. On the other hand, underinvestment can lead to the opposite situation. It is evident therefore that the economic and the reliability constraints can be compitative, and this can lead to difficult managerial decisions during both the planning and the operating phases.

1.1 Power System Reliability

Power system reliability assessment, both deterministic and probabilistic, deals with the two basic aspects, namely, system adequacy and system security.

Adequacy relates the existence of sufficient facilities within the system to satisfy the consumer load demand or system operational constraints. These include the facility necessary to generate sufficient energy and the associated transmission and distribution facilities required to transport the energy to the actual consumer load points. Adequacy is therefore, associated with static conditions which do not include the system disturbances.

Security relates the ability of the system to respond to disturbances arising within the system. Security is therefore, associated with the response of the system to whatever perturbation it is subjected to. These include the condition with local and widespread disturbances and the loss of major generation and transmission facilities.

This thesis concerns with the adequacy of the electric power system.The basic techniques for the adequacy assessment can be categorized in terms of their application to segments of a complete power system [5]. These segments are defined as functional zones: generation, transmission and distribution. This division is most appropriate as most utilities are either divided into these zones for purpose of organization, planning, operation and/or analysis.

It is therefore, convenient to assess the adequacy of the power system by dividing it into different functional zones, namely, generation, transmission and distribution.

In Hierarchical level 1 (HL1), it is assumed that the transmission facilities are available all the time in the system and the adequacy of the power system is evaluated by considering the generator outages in the system. At this level, the frequency, the mean duration and the probability which is associated with the various levels of generating capacity are evaluated [6].

HL2 studies, also called composite power system studies, can be used to assess the adequacy of an existing or proposed composite system including the impact of various reinforcement alternatives at both the generation and the transmission levels. These effects can be assessed by evaluating two sets of indices namely, individual bus indices and system indices. The system indices give an assessment of overall adequacy and the load point indices monitor the effect on individual buses and provide input values to the next hierarchical level [7] .

HL3 considers the assessment of distribution systems and general economic constraints. It would enable the effect of generation, transmission and distribution on individual customers to be evaluated and compared against relevant design and operational criteria [8].

The enormous size of the power system has become an obstacle against many essential studies and analysis. Load flow calculations are essential and have to be conducted periodically to ensure the proper functioning of the system. Taking that into consideration, reliability studies require the utilization of load flow for every selected state, which lead the planners to face a very difficult task in finding a compromise between the accuracy and speed [5, 9].

1.2 Adequacy Assessment of A Composite Power System

A wide range of techniques have been proposed for the reliability assessment of a composite power system. However, these techniques are basically variations of two fundamentally and conceptually different approaches to the problem. These are: Monte Carlo simulation, which is more popular in Europe, and analytical methods which are generally preferred in Great Britain and North America. In this research the analytical approach is used for the adequacy evaluation of power systems.

Monte Carlo simulation methods consist of randomly selecting the state of both system component and load and a subsequent compotation of reliability index for theses simulated states [4].

1.3 Analytical Methods

Analytical methods for reliability evaluation of power systems require much less computer time than Monte Carlo techniques. This section presents a brief description of the principles involved in analytical methods.

These techniques are probabilstic reliability procedures which attempt to assess the risk of system failure(unavailability) on the basis of outage statistics of system components. The basic steps involved in any analytical approach used for system reliability adequacy assessment are:

1. Selection of System States.

   A system state(combination of generators, lines and transformers on outage)is selected by any suitable method. The main methods used are contingency ranking, minimum state probability or frequency of occurance and contingency order.

2. Simulation of System Operating Condition.

   Following the selection of certain state, some means of modelling the system is required to determine the operating conditions. The most common method used for this purpose include the network flow model, the DC load flow, and the AC load flow. The choice of method depends on the objective of the study. A DC load flow or network flow method model can be used if the system problems to be detected are restricted to circuit overloads and system islanding. An AC load flow is used if voltages are to be computed and reactive power flows are to be considered [10].

3. Detection of System Problems.

   The detection of system problems is an essential feature of any algorithm for composite power system reliability studies. The most common criteria used for defining a system problem are: line or transformer overloading, insufficient generation, system islanding and voltage violations.

4. Relief actions.

   After detecting a system problem, some corrective or relief actions may be adopted to alleviate such a condition. The relief actions include adjustment of voltages, generation redispatch and load curtailment.

5. Computation Of Severity.

   The computation of severity of any system problem can be calculated in terms of the amount of load or energy curtailed or any other suitable index.

6. Cumulation Of Reliability Indices.

   The event probabilities and frequencies are cumulated into system and load point indices., These indices can be formed by either all the system states analysed(failure or successes) or only the states that led to the system failure (failures).

These indices are utilized to assess the system reliability during planning of power systems.

1.4 Adequacy Indices

The adequacy evaluation of a composite power system can be best expressed by producing indices both for the system and for the individual load points. An outage events may affect a wide area of the system or it may affect a small group of buses or perhaps a single bus. This depends upon the components under outage, their relative importance and location in the network configuration, the corrective actions taken and the load curtailment philosophy etc. The adequacy indices should focus attention on those portions of the system that are directly affected by the outage of the element(s). The total contribution of all possible outage contingencies considered should indicate those areas in the system which are less reliable and are prone to disturbances. The fundamental reliability indices are:

- The probability of being in a particular state,
- Its frequency of occurance, and
- If a reduction in load is required, the corresponding energy not supplied.

The reliability indices in general can be classified into three groups:

1. System indices,

2. Load point indices,

3. Line reliability information index.

1.4.1 System Indices

The over all system indices provide a measure of the adequacy of the composite power system to meet its total load demand and energy requirements and are quite useful to the system planner and manager. Therefore, these indices provide useful guidelines as they represent the behavior of the entire system and hence clearly identify global problems; e.g. scarce generation, lines prone to overload, etc. It must be recognized, however, that it may be difficult and some times misleading to draw conclusion about the system adequacy from the indices of a single bus.

1.4.2 Load Curtailment Indices

The annualised and annual indices [5] provide information regarding the number of load curtailments and the total load curtailed at each bus and for over all system. From these indices, it is difficult to find out how many times a particular amount of load at each bus is to be curtailed. The amount of curtailable load at any bus may vary from one system to another. This amount may even be different in a given system at different periods of the year. It is, therefore, desirable to calculate load curtailment probability and frequency indices for a system as a function of MW load curtailed [11].

1.4.3 Line and Load Point Indices

Calculation of system indices only does not convey localized information. The other two groups of indices, load point and line reliability results, help to identify specific weaknesses of the network and zones requiring possible reinforcement and the effect of the individual reinforcement due to the behavior of the individual loads. Therefore, these indices provide useful guidelines in designing a system and in comparing alternate system configurations and system modifications. The individual load point indices are very dependent on the selection of the load curtailed philosophy. Depending upon the relative priority given to the buses in a system, the load can be curtailed accordingly, when ever there is a capacity deficiency in the system [11, 12].

The need for considering the individual load point indices is also emphasized by the fact that the effect of considering higher level outages is not uniformly distributed over the entire system. At some buses only first and second order outages are sufficient to evaluate the adequacy indices with reasonable accuracy. At other buses, higher level contingencies must be considered before any significant problem is expected [12]

1.4.4 Evaluation of Line Indices

1. Probability of finding an overload in line "l"

$$P_l = \sum_{j \in m} P_{lj} \tag{1.1}$$

Where:

$\sum_{j \in m} \equiv$ States in which an overload of line "l" is detected

$P_l j \equiv$ Probability of the existence of state j.

2. Frequency of occurance of an overload in line "l" is given by:

$$F_l = \sum_{j \in m} f_{lj} \tag{1.2}$$

Where:

$j \in m \equiv$ States in which an overload of line "l" is detected

$f_l j \equiv$ Frequency of the existence of state j.

1.4.5 Evaluation of Load Point Indices

1. Probability of finding a failure condition at bus "k"

$$P_k = \sum_{j \in s} p_j p_{kj} \tag{1.3}$$

2. Frequency of occurance of failure condition at bus "k"

$$F_k = \sum_{j \in s} f_j p_{kj} \tag{1.4}$$

Where:

$j \in s \equiv$ States in which failure condition (load curtailed, busbar isolation) is detected at bus "k".

$f_j \equiv$ The frequency of occurance of outage j,

$p_j \equiv$ The probability of existence of outage j,

$p_{kj} \equiv$ The probability of the load at bus k exceeding the maximum load that can be supplied at that bus during the outage j.

The energy not supplied (ENS) for a particular bus "k" can be calculated by:

$$ENS_k = T \times \sum_{j=1} p_j L_{kj} \tag{1.5}$$

Where:

T $\equiv$ Period of study,

$p_j \equiv$ The probability of a load-shed state,

$L_{kj} \equiv$ Total number of load-shed states.

The total energy-not-supplied (TENS) to the system is then:

$$TENS = \sum_{k=1}^{K} ENS_k \tag{1.6}$$

Where:

$K \equiv$ Total number of load buses.

1.5 Problem Definition

Composite system reliability evaluation involves the joint analysis of generation and bulk transmission facilities which is an important aspect in planning and operation of power systems. When large or interconnected power systems are studied, it is very useful to develop reliability equivalent models for specified sections of these systems. The primary objective of using equivalent models is to replace the large and complex structure of the power system by a simpler model, which retains all the essential elements and possible states of the original system but eliminates much of the detailed information of the system. The equivalent model can then be utilized in further reliability evaluations. The consideration of the required outages, however is severely restricted in practical networks by required computational time, which can be drastically reduced by using the concept of adequacy equivalents since this time increases with the size of the system increases.[5].

1.6 Thesis Organization

The thesis is organized into the following chapters:

The first chapter gives a very general introduction about the concept of the reliability. The second chapter presents a thorough review of the equivalents which are mentioned in the literature before this research. In this chapter the limitations of these equivalents are also discussed which enhances the need of the research towards establishing an AC equivalent for the adequacy analysis. The next chapter presents the mathematical modelling of the network used in this research. The fourth chapter presents the probabilistic nature of the proposed equivalent which is necessary for the evaluation of the adequacy of any network. The fifth chapter will compare the full system and the proposed equivalent system in load flow terms because in adequacy evaluation load flow solution of the power system is required for each state and then that state is defined as success or failure based on the results of load flow analysis. The last chapter is dedicated for the evaluation of the adequacy of the IEEE-24 bus system using the equivalencing approach proposed.

Chapter 2

Literature Review

2.1 Introduction

Power system engineers focused their attention on equivalencing areas which are external to the part of the power system which needs detailed evaluation. Equivalents should be categorized by how they were developed and where they can be used, and not on what they actually represent, since they are supposed to project all the properties of the system in a reduced reference frame [13] . Some of which are described herein

2.1.1 State Space Decomposition

State space of the system can be reduced by state merging technique, state space truncation or sequential truncation [14, 15, 16].

1. **State Merging Technique**

In state merging technique, the number of states of the power system can be reduced by merging them into subsets.The goal in this method is to develop an equivalent transition rates between various subsets.The condition for mergeability are discussed in Ref. [16]. Building the state transition diagram is only possible for a small system but for a large network this procedure becomes impracticable even using modern computer facilities.

2. **State Truncation Technique**

State space truncation technique consists of simply neglecting the states whose contribution to system reliability is insignificant.This is easily achieved when components are independent. However when dependent modes are involved, the decision for deleting the states has to be made prior to formulating and solving the linear equations [14, 15] . This approach suffers the same drawback as has been discussed by the previous technique.

3. **Sequential Merging Technique**

Sequential truncation can be described as the process of building the reliability model by adding components of subsystems, one by one, and deleting the low probability states at each step. Although this method consumes more computational time than the direct state space truncation, it is more manageable. In sequential truncation, the state probabilities are calculated at each step and the state with probabilities less than a reference value are deleted [14].

2.1.2 Adequacy Evaluation of A Small Area In A Large Composite Power System

This approach is suitable for the adequacy evaluation of a large composite power system. The objective of this method is to consider outages in a localized area, and still obtain acceptable results which are close to the values that would be obtained when all credible outages are considered in the system [17].

1. **Hierarchical Approach**

   In this method, the network can be divided into various areas in hierarchical manner as shown in Figure 2.1. The smallest area inside the hierarchical configuration being the area of interest. The indices are calculated for the buses inside the area of interest by considering the outages in that area only. The next area surrounding the smallest area and including it, is then taken to be the new area of interest, which is dealt with in the same manner by considering outages in that area only, and calculating the adequacy indices for the buses inside it. This process continues till the adequacy indices for two such successive networks are within the tolerance limit or the entire system has been scanned [17].

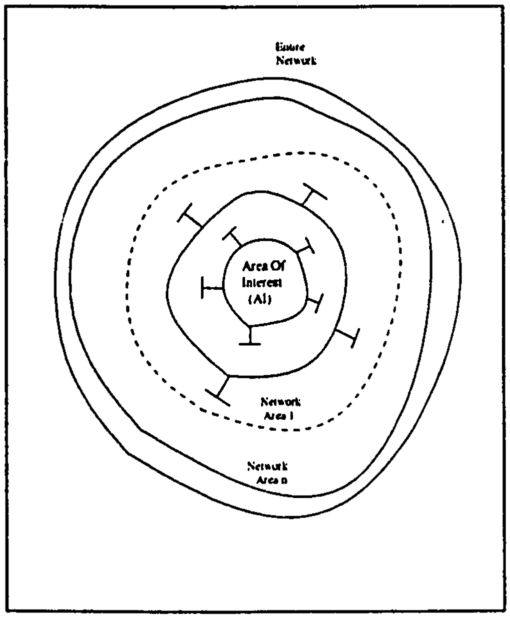

Figure 2.1: Hierarchical Configuration of The Network.

2. **Capacity Margin Table Approach**

In another approach, the problem is solved by developing a generation system equivalent, a transmission system equivalent and finally combining these two equivalents into one generation transmission equivalent [18, 19].This approach is based on making capacity margin tables on the boundary buses of the area of interest, which represents the external network and will be used for the reliability evaluation in the area of interest.

3. **Capacity Outage Probability Table Approach (COPT)**

In an other approach the equivalent generation, transmission and load, deterministic and probabilistic models are represented on the boundary buses

[4]. These models are then utilized to evaluate the adequacy of the area of interest. An alternative approach was presented which established capacity outage probability table on the boundary buses and then utilized these COPTs for the adequacy evaluation of the power system [4].

2.1.3 Limitations In The Existing Approaches

The drawback of hierarchical approach is that the load flow program has to run for the full system for each state during the reliability evaluation, so the computational time is not significantly reduced. Another drawback is the possibility of scanning the entire area. Moreover, the efficiency of these methodologies depend on the size of the small area as compared to the size of the entire network. The efficiency also depends on the network topology, the type of the buses in the small area and the load curtailment philosophy [17].

Capacity Margin technique is more suitable to the radial power systems, however actual power systems are not radial. Therefore, this technique is not suitable for complex mesh structures where generation and load locations are spread over the system [18].

The major drawback in all the adequacy equivalents established earlier, is that they utilize the dc load flow methods for the evaluation of the reliability indices.It is therefore not possible to check the quality (voltage and the reactive power) of the power supply at the major load centers.This limitation arises from the fact that so far it has not been possible to develop a suitable adequacy equivalent using an ac load flow method [20].

2.2 Review Of AC Equivalents

There are however ac equivalents available for different types of power system studies such as:

1. steady state equivalent for the security analysis [21],
2. An external network modelling for on line security analysis [22].
3. Topological equivalent for power systems [13], and
4. Real time external equivalent for on line contingency analysis [23].

2.2.1 WARD Equivalent Approach [1]

In WARD type equivalent the generation in the external system is transformed into current injection and the load of the external system is converted into fixed impedances at the boundary buses. The new model is then utilized for the solution of the network. A power system under steady state conditions is generally modeled as a linear passive network with non-linear components (generators and loads) connecting the various buses to ground. Consider, for a moment, the loads (constant PQ-components) and generators (constant P-$|E|$ components) within the portion of the network to be reduced to equivalent constant admittance and current sources. Approximating these components by constant impedances and/or current sources, then a very simple reduction procedure pioneered by Ward can be used [1].

Kirchoff's current law establishes the following relationship

$$YE = I \tag{2.1}$$

where:

I is the vector of the nodal injections into the linear passive network, E be the vector of the nodal voltages and Y is the nodal admittance matrix.

By the appropriate renumbering of nodes, the first **m** nodes can be used to designate the area of the system to be eliminated, while the remaining **n-m** nodes designate the area to be retained. Further reordering within each area to enhance the sparsity is of course permissible.

Subscript 1 denotes the sub-vector of voltages or currents to be reduced and subscript 2 denote those to be retained. Equation 2.1 can be rewritten as:

$$\begin{bmatrix} Y_{11} & Y_{12} \\ Y_{21} & Y_{22} \end{bmatrix} \begin{bmatrix} E_1 \\ E_2 \end{bmatrix} = \begin{bmatrix} I_1 \\ I_2 \end{bmatrix} \tag{2.2}$$

or in expanded form:

$$Y_{11}E_1 + Y_{12}E_2 = I_1 \tag{2.3}$$

$$Y_{21}E_1 + Y_{22}E_2 = I_2 \tag{2.4}$$

Assume that Y_{11},Y_{12},Y_{21} and I_1 are known and constant. Equation 2.3 can be solved for E_1 and replaced in Equation 2.4. After re-arranging

$$Y_{21}Y_{11}{}^{-1}I_1 \quad + \quad [Y_{22} - Y_{21}Y_{11}{}^{-1}Y_{12}]E_2 = I_2 \tag{2.5}$$

Define:

$$\begin{aligned} I_{2eq} &= I_2 - Y_{21}Y_{11}^{-1}I_1 \\ Y_{22eq} &= Y_{22} - Y_{21}Y_{11}^{-1}Y_{12} \end{aligned} \tag{2.6}$$

Equation 2.5 can be written in the form as:

$$Y_{22eq}E_2 = I_{2eq} \tag{2.7}$$

Eliminating all nodes in the reduced portion creates equivalent branches on all boundary nodes of the retained part. The interior nodes with the retained part are not altered. Similar arguments are applied to the distributed currents.

Using factorization or Gaussian elimination technique, it can be shown that the calculation of Y_{22eq} from Equation 2.6 is equivalent to the partial factorization of Y. In WARD technique the boundary current injection I_2 is changed into constant PQ- loads using the base case voltage.

One disadvantage inherent in this approach involves the properties of reduced generators. The power injected is converted into current injection using the base case solution voltages. The reduced generator is no longer capable of fixed bus voltage magnitude. System changes near the boundary buses of the reduced equivalent often converge to a voltage profile quite different from the full system. The obvious remedy is to retain all the generators in the reduced equivalent area which defeats the purpose of the equivalent [24]

2.2.2 REI Equivalent Approach [2]

The REI net of the radial(R) type, equivalent (E) for a node and independent (I) of the rest of the network is a procedure devised by Dimo [2] to preserve the identity of eliminated generators as the controlled voltage sources. The generators in the reduced part are represented by an equivalent generator. The method is quite similar to the power invariant transformations reported by Tinney et al.[25]

Figure 2.2 illustrates systematical procedure for REI reduction of the generators. As in Ward reduction, these generators can be replaced by constant admittances between the nodes and the zero voltage node $0'$. The value of the admittance is found as the ratio of the known base case generator injection current to the known base case voltage.

$$Y_{gi0'} = \frac{I_{gi}}{E_{gi}} \tag{2.8}$$

where:

$Y_{gi0'}$ is admittance connected to ground at generator bus "i",

I_{gi} is current injected at generator bus i and

E_{gi} is voltage at generator bus i.

The zero voltage node $(0')$ is not the system ground but an isolated node common to all reduced generators. The net current that must be injected into the node $0'$ to keep it at zero volts under base case conditions, is easily calculated as the sum of all generators currents.

$$I_e = \sum I_{gi} \tag{2.9}$$

This current is assumed to flow into 0' from another new node e. The admittance Y_{e0} , connecting these two nodes can be selected in such a manner that the total complex power loss in all admittances $Y_{gi0'}$ plus this new admittance $Y_{e0'}$ is zero. This admittance is thus determined from

$$Y_{e0'} = -\frac{1}{| I_e |^2} \sum \frac{| I_{gi} |^2}{Y_{gi0'}} \tag{2.10}$$

Due to the zero loss requirement, the total complex power injected into the node e is the sum of all generator powers.

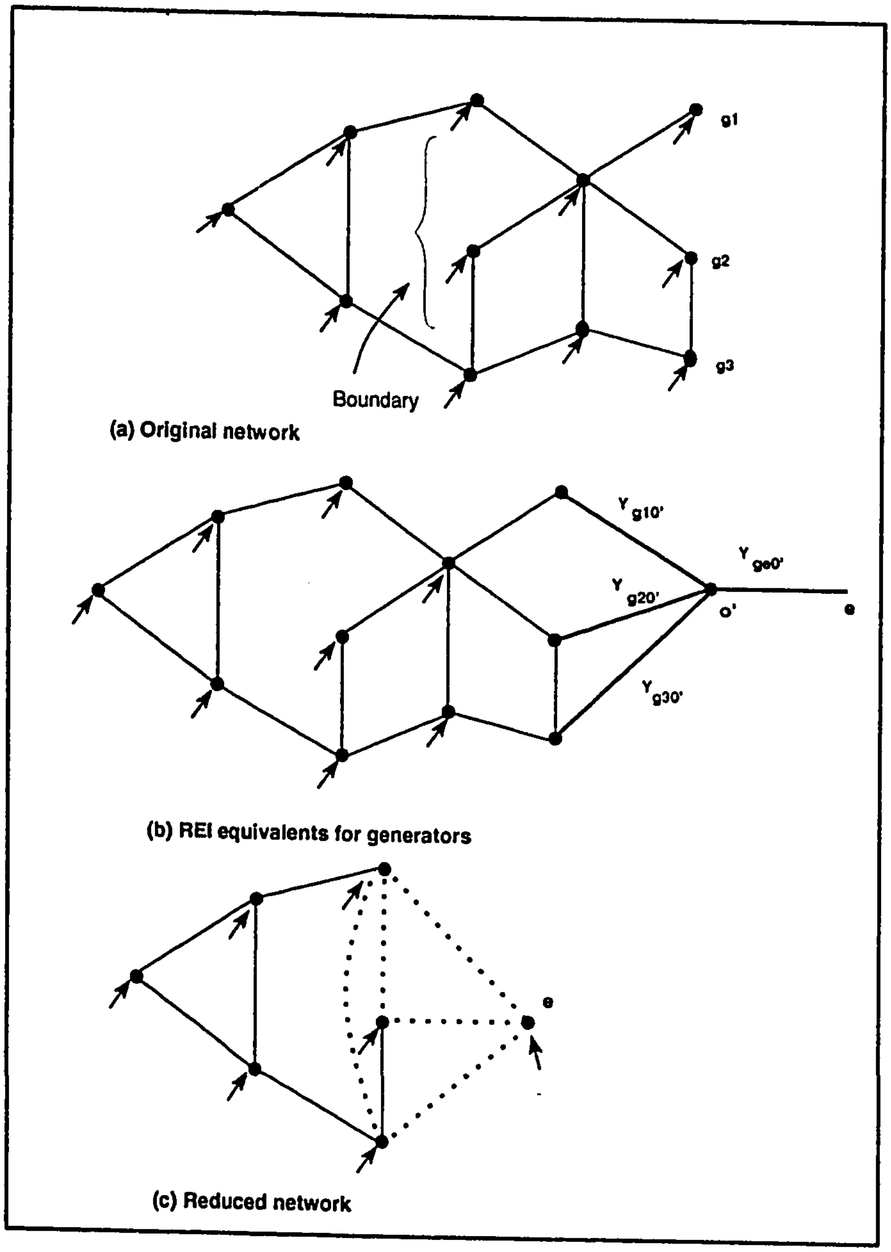

Figure 2.2: The REI Reduction Procedure

$$S_e = \sum S_{gi} \tag{2.11}$$

In particular, this fictitious bus can be treated as a new generation bus with a scheduled generation power equal to $\mathrm{Re}[S_e]$ and schedule voltage magnitude equal to $\mid E_e \mid$. The remaining load buses including the fictitious ground node $0'$ are reduced using the classical reduction technique discussed in previous section.

An excellent survey of load flow equivalencing technique is presented in the References [26, 27, 24, 28]. The main aim of these types of equivalents is to reduce the time of computation to evaluate load flow solutions. The techniques frequently used to improve upon the basic sparsity oriented algorithms are:

- Decoupling : The weak coupling between active and reactive power equations in power flow studies can be exploited [10, 29]. This method results in fast but approximate solutions.

- Partitioning : Also known as tearing or diakoptics [30, 31]. These techniques sub divide the system by removing or "tearing" some of the interconnections [32, 33, 34]. Each part is then analysed independently along with a set of equations that reassemble the system. Diakoptics solutions are exact. This approach permits parallel processing and/or solution of a system when memory resources are limited. Proper programming can result in partitioning that is compatible with the sparsity technique.

- Reduction : In this technique a portion of the system is simply eliminated from all further considerations [1, 2, 35]. Solutions obtained are always approximate unless the reduced portion of the system is linear.

These types of techniques have two basic short comings:

1. If the portion of the system to be reduced is not selected properly, the

amount of computations required to analyse the reduced system can be larger than that required to analyse the original system. [36]

2. As required by the technique if the reduced portion of the network contains any non-linear components(loads or generators), reduction involves approximation. Most reduction techniques do result in a system that agrees perfectly with the unreduced system under one set of conditions(the base case conditions). However if the conditions within the retained portion change (for example, due to line outages or load variations) then the solution obtained from the reduced model does not agree with the one from the exact model.

These equivalents cannot be used for the adequacy analysis as the load and the generation physical concept in the external area were lost.Further more, the concept of statistical parameters for the individual generators in the external area could not be applied to the equivalent generator which is obtained after the equivalencing procedure.

2.3 Load Flow Selection Criteria For Adequacy Analysis

Actually there is no consensus among power utilities regarding uniform failure criteria and, therefore, all utilities do not use the same fundamental solution technique for the load flow.

Because of the basic differences between power systems, and usually different operating policies, it is not possible to formulate a general criteria, but it is possible to define some basic failure criteria for the power system. A method for the solution of the network(power system) will be selected, considering the required parameters needed for the evaluation of the indices based on the failure criteria. The actual system conditions have to be properly checked for all possible malfunctions, or out-of-limit operating conditions., These operating conditions define the failure state of the system, most commonly used conditions are:

1. Lack of sufficient generation,

2. Component over loading,

3. Isolation of the system bus,

4. Voltage violation, and

5. Reactive power violation

The selection of the type of load flow methods depends, on the adequacy indices which are to be calculated. The concept of 'equivalent' was only utilized for DC load flow method, which could not provide enough information about the exact operating condition of the system. AC load flow method can provide adequacy indices for all above failure solutions, while DC load flow models can provide indices only for failure states 1, 2 and 3. Fig. 2.3 shows recommended failure criteria for the three solution techniques described earlier[17]. Failure criteria of either the network flow method or the DC load flow method are the subset of the failure criteria of the AC load flow methods.

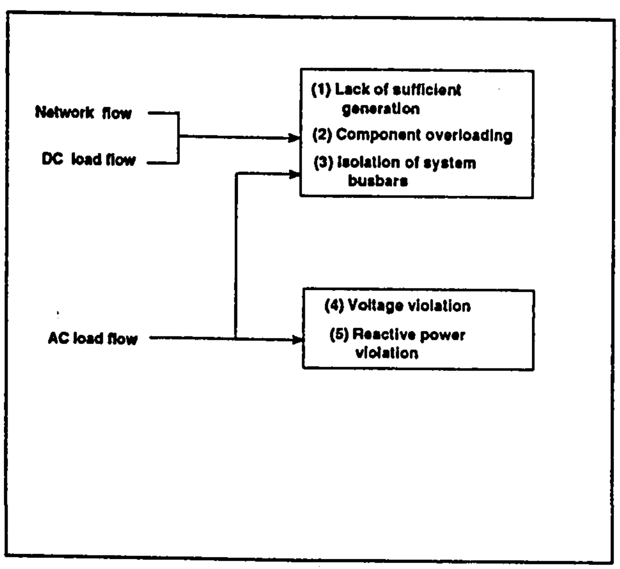

Figure 2.3: Failure Criteria For Different Methods.

2.4 Thesis Objectives

The main objective of this thesis is to propose a new efficient technique, which can be used to study the adequacy of large power system. The approach utilizes an adequacy equivalent models developed for an interconnected area (IA) which can be used for solving higher level outages in the area of interest (AI). The basic relationship between the IA and the AI is shown in the Fig. 2.4

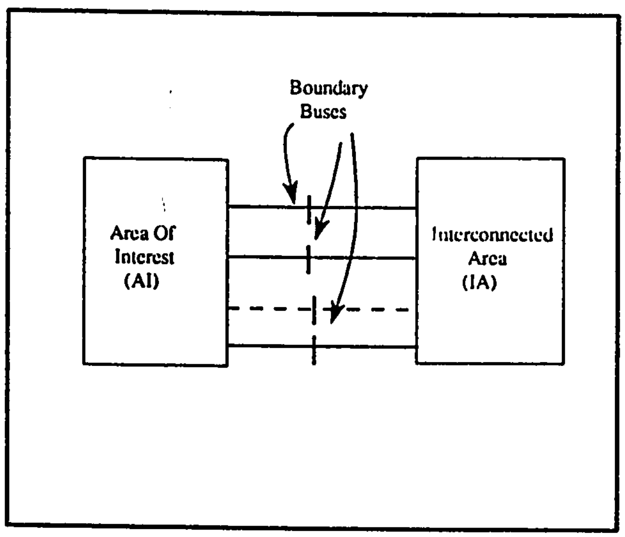

Figure 2.4: Concept of The Area of Interest And Interconnected Area .

Figure 2.5 explains in details the concept of the adequacy equivalent which represents the external system and could be used for the adequacy evaluation of the composite power system.

In the preceding sections, it has been observed that there are various adequacy equivalents which have been utilized for the reliability evaluation of the

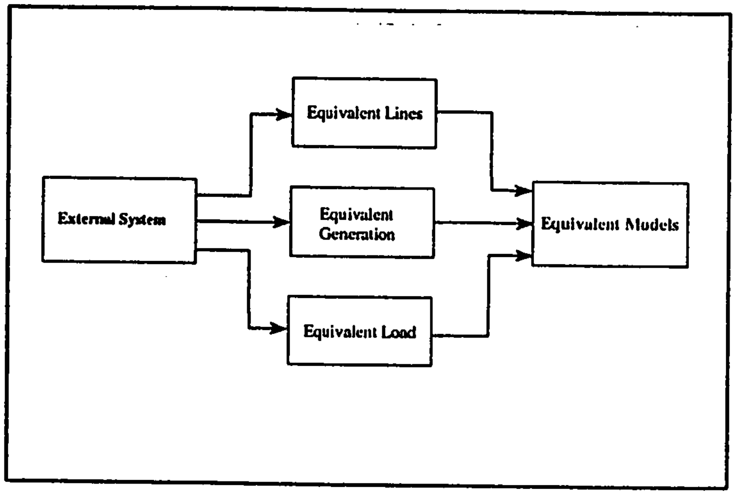

Figure 2.5: Equivalencing Approach.

composite power system. The major drawback of these equivalents is that they can utilize the dc load flow methods, and thus fail to provide any information on voltage profile and the reactive flows in the area of interest. They could only be used to obtain information on the active flow limits of the transmission lines in the area of interest. For a full information regarding the adequacy of the power system, one should also check the quality of the power system, one should have an ac equivalent which can be used for the ac load flow to obtain the information about the adequacy of the system. This thesis is aimed at proposing a new ac equivalent model which attempts to rectify the shortcoming of the previously proposed techniques while retaining an acceptable degree of accuracy.

Chapter 3

Deterministic Modelling Of Power System Equivalent

3.1 Introduction

Power system consists of a large number of components (generating units, transmission facilities, transformers and other components) that may need to be included in the reliability study. The IEEE-RTS has 34 transmission facilities, and thirty two generating units. Therefore, the total number of components is sixty six, and the total number of states will be 2^{n} $=7.3\times10^{19}$. Modern power systems have lot more components than IEEE-RTS. Therefore the main problem for a large system is the size of the state space. As the number of system states is a major factor in the time required to achieve adequacy evaluation, a load flow calculation is necessary for each simulated state. The concept of "adequacy equivalent" is employed to decrease the computational time required for the adequacy evaluation of the composite power system [4, 19, 17]. But if it is required to check the quality of the power supply these equivalents cannot be utilized because they could only utilize the DC load flow method which fails to provide any information about the quality of the supply. The main objective of this research is to come up with a new equivalent which can utilize an AC load flow so that the computational time could be reduced when the quality is also of concern in adequacy analysis.

3.2 Equivalent Model

Ac equivalent model can be achieved after applying reduction technique to a composite power system. Equivalents for adequacy studies are of two types: Deterministic equivalent and probabilistic equivalent. The deterministic equivalent model is defined as a reduced approximate system in which the required information can be given as nearly as possible to the behavior of actual unreduced system, without including any statistical parameter of the reduced external system in the modelling process.

The probabilistic equivalent model is defined as a deterministic equivalent model but also includes the probabilistic nature of all the components of the external system, e.g. mean time to failure (MTTF) and mean time to repair (MTTR).

The inclusion of the statistical behavior gives the new equivalent model the ability to include the component stochastic variations, which results in a more realistic equivalent model.

In the proposed technique the external generation, load and transmission components are presented at the boundary buses in this way, where the variation of load and generation in the external system can be realized for the adequacy evaluation of the power system. The generator buses are selected as the boundary buses between the internal and the external area. These equivalent models will represent the external area at the boundary buses. Adequacy analysis will be conducted using these equivalent models.

3.3 Proposed Network Reduction Method

Gaussian elimination is used as the basic step for the equivalencing technique. The system is divided into three areas. These are is classified as the internal area, the boundary area and the external area. The buses to be eliminated are included in the external area. The resulting network, after the equivalencing procedure, consists of the boundary buses and the area of interest.

An interconnected power system is shown in Figure 3.1.

where:

T_1, T_2 and T_3 are the Tie lines,

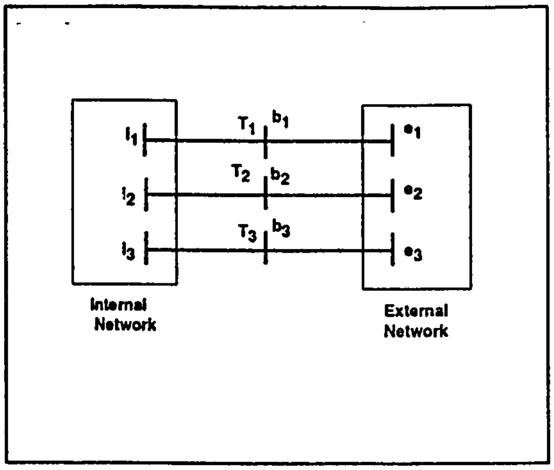

Figure 3.1: Interconnected Power System

i_1, i_2 and i_3 are the Internal network buses, and

b_1, b_2 and b_3 are the external boundary buses,

Nodal voltage equations for the system can be written in matrix form.

$$\begin{bmatrix} Y_{ii} & Y_{ib} & 0 \\ Y_{bi} & Y_{bb} & Y_{be} \\ 0 & Y_{eb} & Y_{ee} \end{bmatrix} \cdot \begin{bmatrix} V_i \\ V_b \\ V_e \end{bmatrix} = \begin{bmatrix} I_i \\ I_b \\ I_e \end{bmatrix} \tag{3.1}$$

Where:

i represents the internal area buses,

b represents the boundary area buses, and

e represents the external buses.

The elimination of the external network buses is obtained by reducing the external network row and column in the nodal admittance matrix [Y], using the general formula of Gaussian elimination. Hence equation 3.1 becomes

$$\begin{bmatrix} Y_{ii} & Y_{ib} \\ Y_{bi} & Y'_{bb} \end{bmatrix} \cdot \begin{bmatrix} V_i \\ V_b \end{bmatrix} = \begin{bmatrix} I_i \\ I_b' \end{bmatrix} \tag{3.2}$$

Consider Equation 3.1 and rewrite them in the following linear form.

$$\begin{aligned} Y_{ii}V_i &+ Y_{ib}V_b & &= I_i \\ Y_{bi}V_i &+ Y_{bb}V_b &+ Y_{be}V_e &= I_b \\ & Y_{eb}V_b &+ Y_{ee}V_e &= I_e \end{aligned} \tag{3.3}$$

From equation 3.3

$$V_e = Y_{ee}^{-1}(I_e - Y_{eb}V_b) \tag{3.4}$$

Substituting equation 3.4 into equation 3.3 ,

$$Y_{bi}V_i + Y_{bb}V_b + Y_{be}Y_{ee}^{-1}(I_e - Y_{eb}V_b) = I_b \tag{3.5}$$

$$Y_{bi}V_i + (Y_{bb} - Y_{be}Y_{ee}^{-1}Y_{eb})V_b = (I_b - Y_{be}Y_{ee}^{-1}I_c) \tag{3.6}$$

Hence, the linear equation 3.3 can be written as:

$$Y_{ii}V_i + Y_{ib}V_b = I_i \tag{3.7}$$

$$Y_{bi}V_i + (Y_{bb} - Y_{be}Y_{ee}{}^{-1}Y_{eb})V_b = (I_b - Y_{be}Y_{ee}^{-1}I_e) \tag{3.8}$$

Then

$$Y'_{bb} = (Y_{bb} - Y_{be}Y_{ee}^{-1}Y_{eb}) \tag{3.9}$$

After the elimination of the external network, the new boundary admittance matrix is:

$$[Y_{bb}^{new}] = \{\left[Y_{bb}^{old}\right] - [Y_r]\,[Y_{eb}]\} \tag{3.10}$$

$$[Y_r] = \{[Y_{be}][Y_{ee}{}^{-1}]\} \tag{3.11}$$

where:

$[Y_{bb}^{new}]$ is the bus equivalent boundary admittance matrix,

$[Y_{bb}^{old}]$ is the bus original boundary admittance matrix,

$[Y_r]$ is the resultant matrix produced as a result of the multiplication of the boundary to external area admittance matrix (Y_{be}) by the external area bus matrix(Y_{ee}^{-1}).

$[Y_{eb}]$ is the external to boundary admittance matrix.

3.4 Equivalent Transmission Representation At The Boundary Buses "Deterministic Approach".

The equivalent boundary transmission at the boundary buses can be obtained from Equation 3.10 . The dimension of the boundary matrix is directly related to the number of boundary busbars. In the deterministic approach the equivalent line impedance is calculated on the assumption that all the external lines are available. There is no external stochastic transmission effect included for the evaluation of the equivalent transmission model.

3.5 Equivalent Generation Representation At The Boundary Buses.

3.5.1 Equivalent Active Generation

The generating units inside the external area are represented by equivalent generating units at each boundary bus. The shifting of the external generating units to the boundary buses is achieved by using the idea of the generation distribution ratio [4]. Flow distribution ratio can be defined as :

" The ratio of injection to each boudary bus, subjected to one unit injection from an external bus"

The number of these equivalent units at each boundary bus is equal to the number of generating units at the external buses.

This modelling gives the flexibility to deal with these equivalents as physical units. Another advantage is that the units at a distance, which have a very little effect on the area of interest, can be ignored and not be considered during the analysis. Also the units that show a good history of continuous operation can, if possible, be ignored [4]. Although the equivalent units at the boundary busbars are equal to the same number of units at the external busbars, the overall computational time is reduced because computational time needed to solve line outages is more than the time required to solve generator outages[37].

The solution of load flow problems, in polar coordinates, by Newton Raphson method, involves an iterative solution of the following coupled linear equations:

$$\begin{bmatrix} \Delta P \\ \Delta Q \end{bmatrix} = \begin{bmatrix} \partial P/\partial\delta & \partial P/\partial V \\ \partial Q/\partial\delta & \partial Q/\partial V \end{bmatrix} \begin{bmatrix} \Delta\delta \\ \Delta V \end{bmatrix} = \begin{bmatrix} H & N \\ J & L \end{bmatrix} \begin{bmatrix} \Delta\delta \\ \Delta V \end{bmatrix} \tag{3.12}$$

The decoupled Newton method is derived from equation 3.12 by neglecting the Newton subjacobeans N and J completely. This results in the following decoupled ($P-\delta$)and (Q-V) loads flow equations:

$$[\Delta P] = [H][\Delta\delta] \tag{3.13}$$

$$[\Delta Q] = [L][\Delta V] \tag{3.14}$$

It is worth mentioning here that the elements of the coupling jacobeans N and J becomes negligible when the conditions $R \ll X$ is satisfied for all the branches of the system. The well known FDLF method [10] is derived from Equations 3.13 and 3.14 with the following further assumptions.

1. The magnitude of all bus voltages are close to unity. The angle difference between two bus voltages is very small such that $cos\delta_{ij} \simeq 1.0$. The R/X ratio of all branches is negligible, such that $G_{ij}sin\delta_{ij} \ll B_{ij}$. The bus reactive powers are very small as compared to the corresponding diagonal elements of the B matrix. Here B is the imaginary part of the admittance matrix Y.

2. Branch resistances, transformer off-nominal tap settings and shunt admittances are neglected while the coefficient matrix H of the P- δ is formed. The effect of phase shifting transformers is neglected in the L matrix of the Q-V problem. The normalized active ($\Delta P/ V$) and reactive ($\Delta Q/V$) power mismatches are used on the LHS of the $P - \delta$ and Q-V problems, respectively [38].

The elements of Jacobeans will become

$$\partial P/\partial \delta = B' \tag{3.15}$$

and,

$$\partial Q/\partial V = B'' \tag{3.16}$$

These partial differenial equations 3.15 and 3.16 can be solved by using above assumptions the following equations can be obtained.

$$[P] = [B'][\delta] \tag{3.17}$$

$$[Q] = [B''][V] \tag{3.18}$$

If the network is divided into internal, boundary and external area then the above Equations 3.17 is presented in the matrix form as:

$$\begin{bmatrix} B'_{bb} & B'_{bc} \\ B'_{eb} & B'_{ce} \end{bmatrix} \begin{bmatrix} \delta_b \\ \delta_e \end{bmatrix} = \begin{bmatrix} P_t \\ P_e \end{bmatrix} \tag{3.19}$$

where P_t is active power inside area of interest and P_e is the active power in the external area.

In linear form, equation 3.19 can be represented as

$$P_t = B'_{bb}\delta_b + B'_{bc}\delta_e \tag{3.20}$$

$$P_e = B'_{eb}\delta_b + B'_{ce}\delta_e \tag{3.21}$$

From Equation 3.21

$$B'_{ee}\delta_e = P_e - B'_{eb}\delta_b \tag{3.22}$$

$$\delta_e = B_{ee}^{-1}P_e - B_{ee}^{-1}B'_{eb}\delta_b \tag{3.23}$$

Replacing the value in Equation 3.20. We get

$$P_t = B'_{bb}\delta_b + B'_{be}{B'_{ee}}^{-1}P_e - B'_{be}{B'_{ee}}^{-1}B'_{eb}\delta_b \tag{3.24}$$

$$P_t = (B'_{bb} - B'_{be}{B'_{ee}}^{-1}B'_{eb})\delta_b + B'_{be}{B'_{ee}}^{-1}P_e \tag{3.25}$$

$$P_t = B'_r\delta_b + P'_e \tag{3.26}$$

Hence the physical generation in the external system could be represented at the boundary buses by the following formula,

$$P'_e = B'_{be}{B'_{ee}}^{-1}P_e \tag{3.27}$$

$$P'_e = B'_{rr} P_e$$

$$B'_{rr} = B'_{be} {B'_{ee}}^{-1} \tag{3.28}$$

where:

P'_e is the column vector to provide the equivalent amount of injection from each unit,i, of the external generation busbar to the boundary buses. The same equation is used to calculate the generation-distribution ratio.

P_e is the external generation.

Equation 3.27 can be specified as the flow-distribution ratio.

The advantage of the flow distribution ratio is that the knowledge of the ratio flows to the boundary buses from each external generation bus helps in predicting the exact equivalent generation, without calculating the equivalent generation each time the external generation changes. Equation 3.27 is used to determine the ratio flow (MW) from each external generation bus to the boundary bus. However, it must be recognized from Equation 3.27 that the equivalent generation at each boundary bus is dependent on the amount of injection from the external generating units. That is, the generation at a given external unit is distributed among the defined boundary buses according to Equation 3.27. But in contrast the amount of injection at the boundary buses have the same statistical parameters as those of each external unit, i.e. each external unit is represented by an equivalent dependent injections (due to each external unit), have the same statistical parameters (MTTR, MTTF) as their original external units.

The net equivalent generation model at the boundary buses is calculated as follows:

$$[PG_b{}^{new}] = \left[PG_b{}^{old} - PG_{bi}\right] \tag{3.29}$$

where:

$PG_b{}^{new}$ is the net equivalent generation at the boundary bases,

$PG_b{}^{old}$ is the generation if any, at the boundary bases,

PG_{bi} is defined in equation 3.27 as P_e'

3.5.2 Equivalent MVAR limits Of The External Generators Represented At The Boundary Buses

For the ac analysis it is necessary to represent the external MVAR generating capability of the generators so as to keep checking their MVARs generating capability. The concept of flow distribution ratios is again utilized for the evaluation of the MVAR capability.

From equation 3.18,

$$[Q] = [B''][V] \tag{3.30}$$

By following the same procedure we could get

$$\begin{bmatrix} B''_{bb} & B''_{be} \\ B''_{eb} & B''_{ee} \end{bmatrix} \begin{bmatrix} V_b \\ V_e \end{bmatrix} = \begin{bmatrix} Q_t \\ Q_e \end{bmatrix} \tag{3.31}$$

where Q_t and Q_e are the reactive generation in the area of interest and in the external area respectively.

In linear form of equations, Equation 3.31 can be represented as

$$Q_t = B''_{bb}V_b + B''_{be}V_e \qquad (3.32)$$

$$Q_e = B''_{eb}V_b + B''_{ee}V_e \qquad (3.33)$$

From Equation 3.33

$$B''_{ee}V_e = Q_e - B''_{eb}V_b \qquad (3.34)$$

$$V_e = B''^{-1}_{ee}Q_e - B''^{-1}_{ee}B''_{eb}V_b \qquad (3.35)$$

Substituting equation 3.35 into equation 3.32, we get

$$Q_t = B_{bb}''V_b + B_{be}''B''^{-1}_{ee}Q_e - B''_{be}B''^{-1}_{ee}B''_{eb}V_b \qquad (3.36)$$

$$Q_t = (B''_{bb} - B''_{be}B''^{-1}_{ee}B_{eb}'')V_b + B''_{be}B_{ee}''^{-1}Q_e \qquad (3.37)$$

$$Q_t = B''_r V_b + Q_e' \qquad (3.38)$$

Hence the reactive generation in the external system can be presented at the boundary buses by the following formula:

$$Q'_e = B''_{be} B''^{-1}_{ee} Q_e \tag{3.39}$$

$$Q'_e = B''_{rr} Q_c$$

$$B''_{rr} = B''_{bc} B''^{-1}_{ec} \tag{3.40}$$

where:

$Q_e{}'$ is a column vector to provide the equivalent reactive power injection from each unit, i, of the external generation busbar to the boundary buses. The same equation is used to calculate the generation-distribution ratio.

Q_e is the external generation (MVAR).

3.6 Equivalent Load Representation At The Boundary Busbars " Deterministic Modelling "

The external load is represented at the boundary buses by an equivalent total load. Therefore, at each boundary bus there will be only one value to represent the total load of the external area. The equivalent model will represent active and reactive loads because both are necessary for the evaluation of the adequacy analysis using AC load flow.

As the load of any bus can be represented by negative injection therefore the load model for the external load can be achieved by using the same concept as described in section 3.5.

The equivalent load model of the external load buses at the boundary bus, is calculated as follows:

1. For the active load

The flow distribution ratio calculated for active generation ca be utilized to calculate the equivalent active load which will represent the load in the external area, at the boundary buses.

$$[L_{bip}] = [B'_{rr}.L_{ep}] \tag{3.41}$$

where

L_{bip} is a column vector to provide the equivalent amount of active load from each external load busbar, i, to the boundary buses. The same equation can be used to calculate the load-distribution ratio for the active loads in the external network. B'_{rr} is described by equation 3.28, L_{ep} is the active load of the external area.

2. For the reactive load

The flow distribution ration used for reactive generation model ca be utilized for evaluation of equivalent reactive which represents the load in the external area, at the boundary buses.

$$[L_{biq}] = [B''_{rr} L_{eq}] \tag{3.42}$$

where

L_{biq} is a column vector to provide the equivalent amount of reactive load from each external load bus, i, to the boundary buses. The same equation can be used to calculate the load-distribution ratio for the reactive loads in the external network.

B''_{rr} is described by equation 3.40,

L_{eq} is the reactive load of the external area.

The net equivalent active load model at the boundary buses is calculated as shown in equation 3.43

$$\left[L_{bp}^{new}\right] = \left[L_{bp}^{old} - L_{bip}\right] \tag{3.43}$$

Where

L_{bp}^{old} is the active load if any at the boundary buses,

L_{bp}^{new} is the net equivalent load at the boundary buses(active).

The net equivalent reactive load model at the boundary buses is calculated as shown in equation 3.44

$$\left[L_{bq}^{new}\right] = \left[L_{bq}^{old} - L_{biq}\right] \tag{3.44}$$

Where

L_{bq}^{old} is the reactive load if any at the boundary buses,

L_{bq}^{new} is the net equivalent load at the boundary buses(reactive).

The concept of load distribution ratio helps in varying the equivalent load model at the boundary buses with the variation of the load in the external area.

The equivalent model established in the thesis can also account for load and generation variation in the external area. If there is any load variation on any of the external buses, utilising the concept of distribution ratio, that load variation can be modeled at the boundary buses.

Chapter 4

Probabilistic Modelling of Power System Equivalent

4.1 Introduction

In the previous chapter the "Deterministic Equivalent" models are formulated in which , no information about the stochastic behaviour of the transmission components were considered which are necessary for a realistic evaluation of the adequacy assessment of power systems. The uncertainties in the transmission components of the external system are considered in the process of establishing the equivalent models. It is assumed that the failure of the generating unit and the failure of the transmission lines are statistically independent. However, two steps are taken before reaching the statistical mean equivalent models. The first one is to calculate the equivalent component of the external based on the assumption that all the transmission facilities in the external area are available. The second one is to calculate the equivalent components of the external area for any desirable outage of the external area. For simplicity, the state probability (availability and unavailability) is calculated beforehand for the outage of each transmission component that belongs to the external system. Therefore the final probabilistic equivalent model reflects the fluctuation of the external system.

4.2 Stochastic External Transmission Effect On The Equivalent Boundary Lines

In forming the equivalent probabilistic model of the equivalent boundary line probabilistic values of the transmission lines of the external area are taken into consideration. Since each line in the external area has a mean time to failure MTTF, and a mean time to repair, MTTR, the probilistic equivalent boundary line(s) are evaluated for the base case and then the outages of the transmission components in the external area are considered.It is assumed that generator and line outages are independent to each other.

In developing the equivalent boundary lines model, in the deterministic case, it was assumed that all lines of the external area are available. This assumption however, is not practical enough. In building the probilistic equivalent at the boundary buses, the availability of the transmission components of the external system is calculated by using the following equation as outages are considered to be independent.

$$P_s = \prod_{i=1}^{k} R_i \tag{4.1}$$

where:

P_s is the availability of the transmission components of the external area in the base case,

R_i is the availability of the transmission component i.

Multiply equation 4.1 by equation 3.10, we get

$$[Y_{bb}^{pnew}] = P_s \times \left\{ \left[Y_{bb}^{old}\right] - [Y_r]\,[Y_{eb}] \right\} \tag{4.2}$$

$$[Y_r] = \{[Y_{be}][Y_{ee}{}^{-1}]\} \tag{4.3}$$

where:

Y_{bb}^{pnew} is the bus equivalent probilistic admittance boundary matrix.

As expected value can be calculated as:

$$E\{X\} = P_i X_i \tag{4.4}$$

where E{X} is the expected value of admittance in equation 4.2.

4.2.1 Statistical Mean Equivalent Boundary Line(s) Model

Only single line outages are considered in the external system because the probability of the higher order outages are very small. The probability model for considering the outages of the external transmission component is represented by the following equation.

$$P_s = \prod_{i=1}^{k} R_i \prod_{j=1}^{m} Q_j \tag{4.5}$$

where:

P_s is the availability of the transmission component of the external area (subjected to the line outages in the external area),

R_i is the availability of the transmission component i,

Q_j is the unavailability of the transmission component j.

The effect of the outages in the external area is calculated by the mean of all the states that have been considered. The statistical mean value is calculated using the following formula:

$$E\{X\} = \sum_i p_i X_i \tag{4.6}$$

where:

X takes the values X_i with the probility P_i

Therefore the statistical mean equivalent boundary line model will be

$$l_e = \sum_{i=0}^{n} P_i \times l_i \tag{4.7}$$

where:

l_e is the statistical mean equivalent boundary line model,

P_i is the probability of the state that corresponds to the outage of line i,

l_i is the equivalent boundary line corresponding to the outages in the external line i, it is calculated by using Equation 3.10.

4.3 Stochastic External Transmission Effect On The Equivalent Generation Model

The uncertainties in the transmission facilities of the external area is also considered in the proposed generation equivalent model. For the base case probabilistic model, all the transmission facilities in the external system are assumed to be available. It is achieved by multiplying equation 4.1 with equation 3.27 as shown in the following equation.

$$PG_b^p = P_s \times [B'_{rr} P_e] \tag{4.8}$$

where:

PG_b^p is the probabilistic base case equivalent MW generation model,

P_s is the availability of the transmission component in the external area,

Similarly the MVAR probabilistic limit of the generators could be achieved by multiplying equation 4.1 with the MVAR representation at the boundary buses of the external system.

4.3.1 Statistical Mean Equivalent Generating Model

The line outages in the external area is considered while evaluating mean statistical equivalent model. The probability of each line outage is evaluated by equation 4.5 because outages of transmission lines are considered to be independent. Therefore to produce the equation for the statistical mean equivalent generation model, both active and reactive parameters of equation 4.5 is multiplied by equation 3.27 for the active (MW) generation and by equation 3.39 for the reactive generating capability.

1. The equation for the mean equivalent probilistic active generation model is:

$$PG_e = \sum_{i=0}^{n} P_i \times PG_i \tag{4.9}$$

   Where:

   PG_e is the statistical mean equivalent active generation model,

   P_i is the availability of the transmission component in the external area.

   PG_i is the active generation in the external area .

2. For the reactive limit

$$QG_e = \sum_{i=0}^{n} P_i \times QG_i \tag{4.10}$$

   Where:

QG_e is the statistical mean equivalent reactive generation model,

P_i is the availability of the transmission component in the external area.

QG_i is the reactive generation in the external area = Q_i.

4.4 Stochastic External Effect On The Equivalent Load Model

The load model is determined with the assumption that all transmission facilities are available in the external area. Two probabilistic models (active and reactive) are formulated with the line outages in the external area. To include the uncertainties of the transmission facilities, line outages are applied to the external area. For each line outage, the probabilistic equivalent AC load model is calculated as was done in the previous section 4.3.1. In the thesis, only single line outages is considered while evaluating the probabilistic model as the probability of higher order line outages is very small.

For the base case, all the transmission facilities are considered in the external area. This model is achieved by multiplying equation 4.1 by equation 3.41. The equivalent model becomes:

$$[PL_b^p] = P_s \times [B'_{rr}.PL_e] \tag{4.11}$$

Where:

PL_b^p is the equivalent probabilistic active load model,

P_s is the availability of the transmission components in the external area,

PL_e is active load in the external area.

Similarly for the probabilistic reactive load model. Using the same concept as before, the equation will be

$$[QL_b^p] = P_s \times [B''_{r'r'}QL_e] \tag{4.12}$$

Where:

QL_b^p is the equivalent probabilistic reactive load model,

P_s is the availability of the transmission components in the external area,

QL_e is the reactive load in the external area.

4.4.1 Statistical Mean Equivalent Load Model

The mean probabilistic equivalent load models, both for active and reactive loads are calculated by considering the line outages of the external area. Therefore, equations for active and reactive probabilistic load models are:

$$PL_e = \sum_{i=0}^{n} P_i \times PL_i \tag{4.13}$$

$$QL_e = \sum_{i=0}^{n} P_i \times QL_i \tag{4.14}$$

where:

$PL_e \, and \, QL_e$ are the statistical mean equivalent active and reactive load models,

P_i is the probability of the state that corresponds to the outage of the line i in the external area,

PL_i and QL_i are the equivalent active and the reactive load at the boundary buses corresponding to the outage of external line i.

Chapter 5

Load Flow Analysis (Case Studies)

5.1 Introduction

The equivalent technique proposed in the previous chapters is applied to the IEEE 24 bus Reliability Test System (RTS) [3]. Different cases are investigated to validate the equivalent system with respect to load flow. As the major part of adequacy consists of load flow solution for each system state. In this chapter comparison of proposed equivalent model with the full system model is done. The next step will be the application of the equivalent model for the adequacy analysis as will be thoroughly explained in chapter 6, adequacy indices obtained by using the proposed equivalent model with the adequacy indices obtained by the full system, is compared.

For all cases, the original IEEE RTS network is divided into three areas: the external area, the boundary area and the area of interest. The areas of the external and the internal systems are arranged in such a way that both systems are interconnected only through the defined boundary buses where generators are already installed. Comparison of load flow is carried for the area of interest. For each selected case, the AC power flow solution of the equivalent network is compared with the power flow solution of the original network. The statistical characteristic MTTF and MTTR of the lines in the external system are considered while evaluating the statistical mean equivalent component models (As described in the previous chapters 4 and 5).

5.2 Study System-A: Equivalence of The Northern Part of The IEEE-RTS

IEEE- RTS system is shown in Fig.5.2

The external system has 8 lines and 4 buses (17,18,21 and 22). The boundary buses are buses 15 and 16. The rest of the system is chosen as area of the interest. Therefore the 20 bus system is equivalent to 24 bus system. For this study case equivalent model of the north part of the IEEE-RTS system is shown in the Figure 5.3. The equivalent impedance of the boundary line model, the equivalent generation model, and the equivalent load model are shown in Tables 5.1 , 5.2, 5.3 and 5.4

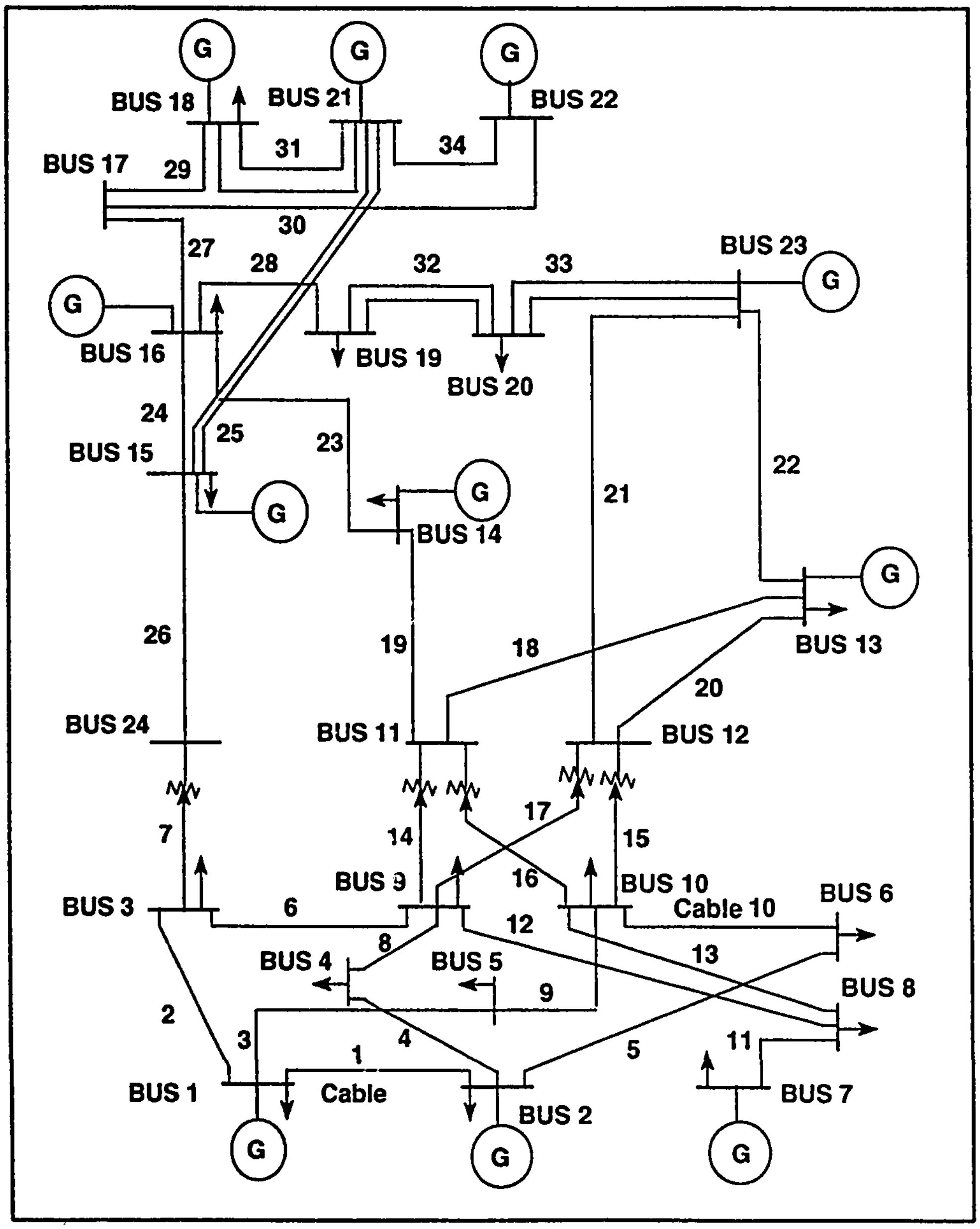

Figure 5.1: IEEE-RTS 24 Bus System [3]

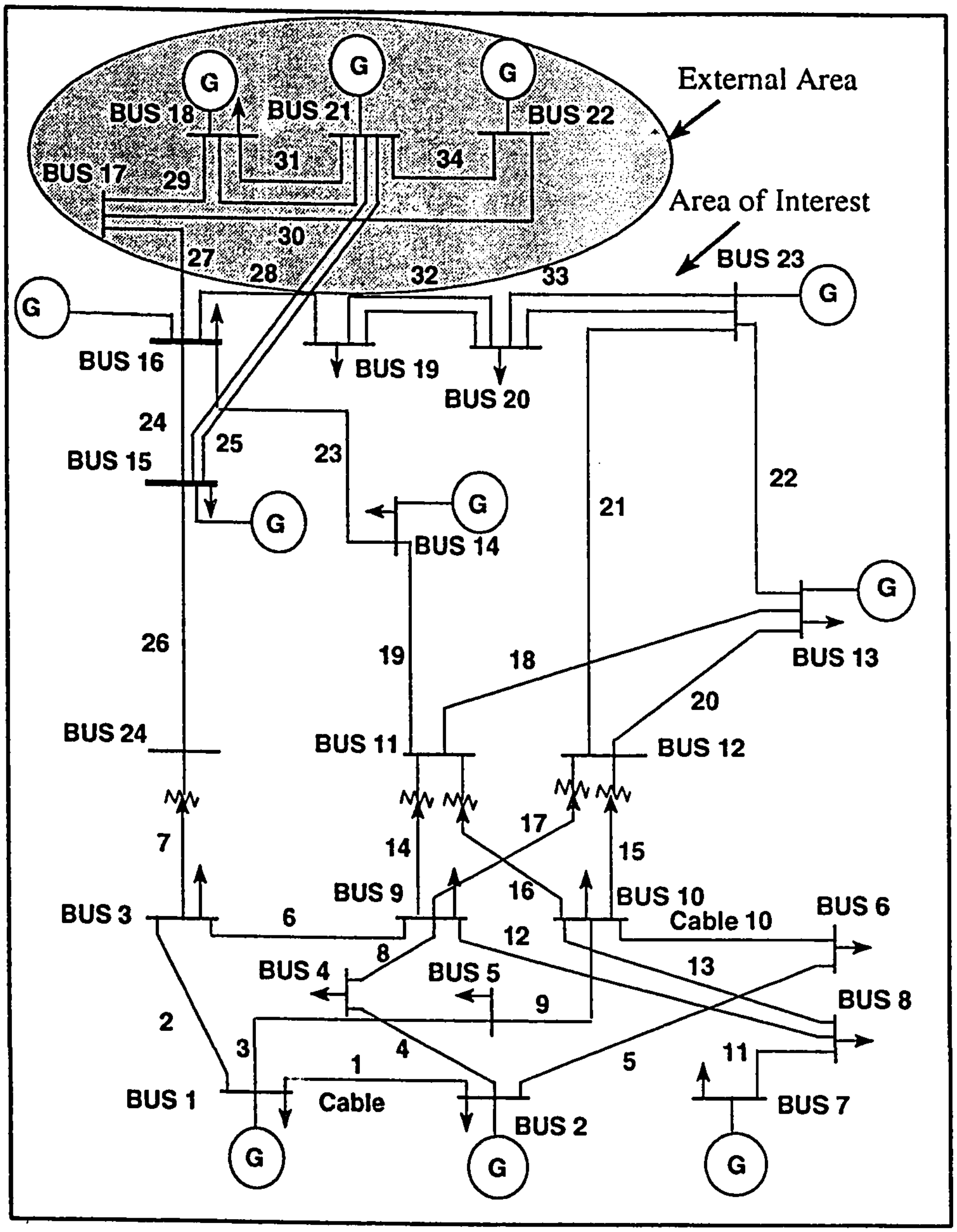

Figure 5.2: External Area For Study System-A

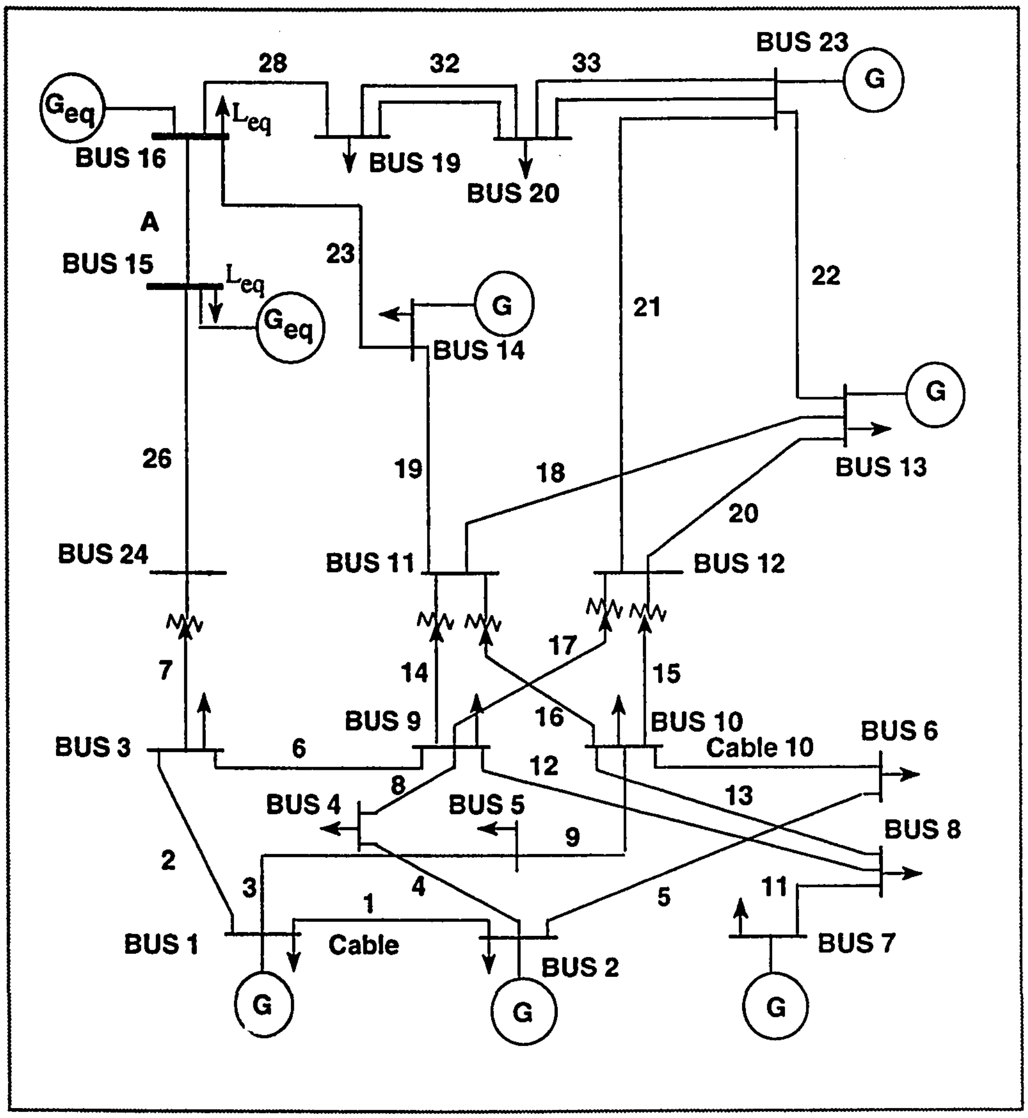

Figure 5.3: Equivalent System of IEEE-RTS 24 Bus System

respectively.

The equivalence process in this case, produces a model of the boundary line connecting the boundary buses 15 and 16 as shown in the Figure 5.3. The base case shows the equivalent boundary lines connecting the boundary buses, when all the lines in the external system are available. The proposed equivalent generation and the equivalent load models are then calculated using techniques, explained in previous chapter. The line outage routine is then applied to the external system. For every line outage, the equivalent boundary line impedance model, the equivalent generation model and the load model at the boundary buses are calculated. Finally, for the base case and line outages(lines: 25,27,29,30,31 and 34) of the external system, the probabilistic equivalent mean models, the boundary line impedance model, the generation model and the load model are calculated. The following tables 5.5 and 5.6 shows the results of load flow analysis. Line A is the factitious bus, obtained after the equivalencing procedure. The maximum error is occurred in the angle of bus 16 which is a boundary bus. S.Bus is sending bus and R.Bus is the receiving bus of the line. As can be seen from tables, % age error is very less then the specified limits. Line 32 and 33 are double circuit lines, hence these are represented by 32D and 33D.

Table 5.1: Equivalent boundary line impedance model at the boundary buses

Contingency order	Line A (Bus15-Bus16) ($p.u.$)	Probability of each state
Base case	$0.00178 + j0.0140$	0.996016
$Line25$	$0.001865 + j0.01468$	$5.15E - 4$
$Line25$	$0.001865 + j0.01468$	$5.15E - 4$
$Line27$	$0.00219 + j0.01729$	$4.39E - 4$
$Line29$	$0.0023 + j0.0016$	$4.00E - 4$
$Line30$	$0.00179 + j0.0141$	$6.78E - 4$
$Line31$	$0.001815 + j0.0143$	$4.39E - 4$
$Line31$	$0.001815 + j0.0143$	$4.39E - 4$
$Line34$	$0.00179 + j0.0143$	$5.62E - 4$
$Meanvalue$	$0.0018 + j0.0140$	$- - -$

Table 5.2: Equivalent generation model at the boundary buses

Contingency order	Boundary bus 15 ($p.u.$)	Boundary bus 16 ($p.u.$)	probability of each state
Base case	6.378	4.621	0.996016
$Line25$	4.792	6.207	$5.15E - 4$
$Line25$	4.792	6.207	$5.15E - 4$
$Line27$	11	0.00	$4.39E - 4$
$Line29$	8.883	2.116	$4.00E - 4$
$Line30$	6.866	4.133	$6.78E - 4$
$Line31$	6.282	4.717	$4.39E - 4$
$Line31$	6.282	4.717	$4.39E - 4$
$Line34$	5.811	5.188	$5.62E - 4$
$Meanvalue$	6.3802	4.6199	

Table 5.3: Equivalent load (active) model at the boundary buses

Contingency order	Boundary bus 15 ($p.u.$)	Boundary bus 16 ($p.u.$)	probability of each state
Base case	1.724	1.605	0.996016
$Line25$	1.295	2.034	$5.15E-4$
$Line25$	1.295	2.034	$5.15E-4$
$Line27$	3.330	3.330	$4.39E-4$
$Line29$	2.964	0.365	$4.00E-4$
$Line30$	1.725	1.604	$6.78E-4$
$Line31$	1.505	1.824	$4.39E-4$
$Line31$	1.505	1.824	$4.39E-4$
$Line34$	1.725	1.604	$5.62E-4$
$Meanvalue$	1.7246	1.6065	$---$

Table 5.4: Equivalent load (reactive) model at the boundary buses

Contingency order	Boundary bus 15 ($p.u.$)	Boundary bus 16 ($p.u.$)	probability of each state
Base case	0.3500	0.3306	0.996016
$Line25$	0.261	0.419	$5.15E-4$
$Line25$	0.261	0.469	$5.15E-4$
$Line27$	0.680	0.00	$4.39E-4$
$Line29$	0.6108	0.076	$4.00E-4$
$Line30$	0.351	0.329	$6.78E-4$
$Line31$	0.310	0.370	$4.39E-4$
$Line31$	0.310	0.370	$4.39E-4$
$Line34$	0.350	0.330	$5.62E-4$
$Meanvalue$	0.3501	0.3305	$---$

Table 5.5: Case-1: Comparison of bus voltages and bus angles for equivalent and full system.

Bus No.	*BusVoltage Original System p.u.*	*BusVoltage Equivalent System p.u.*	*% Error*	*BusAngle Original System deg.*	*BusAngle Equivalent System deg.*	*% Error*
1	1.0000	1.0000	0.00	−21.559	−21.996	1.9
2	1.0000	1.0000	0.00	−21.66	−21.60	0.27
3	0.9484	0.9482	0.00	−18.826	−18.830	0.40
4	0.9599	0.9599	0.00	−23.464	−23.439	0.10
5	0.9942	0.9942	0.00	−23.809	−23.807	0.00
6	1.0431	1.0431	0.00	−26.516	−23.510	0.02
7	1.0000	1.000	0.00	−28.686	−28.686	0.00
8	0.9645	0.9645	0.00	−21.335	−21.211	0.58
9	0.9626	0.9626	0.00	−20.283	−20.285	0.01
10	1.0158	1.0158	0.00	−22.719	−22.685	0.15
11	0.9876	0.9876	0.00	−13.597	−13.594	0.02
12	0.9807	0.9809	0.00	−12.702	−12.704	0.01
13	1.0000	1.0000	0.00	−8.9252	−8.9264	0.01
14	1.0000	1.0000	0.00	−9.847	−9.846	0.01
15	1.0000	1.0000	0.00	−1.168	−1.1674	0.01
16	1.0000	1.0000	0.00	−1.811	−1.882	3.6
19	0.9915	0.9915	0.00	−2.722	−2.734	0.44
20	0.9946	0.9945	0.01	−1.465	−1.468	0.20
23	1.0000	1.000	0.00	0.000	0.000	0.00
24	0.9639	0.9637	0.02	−7.628	−7.638	0.13

Table 5.6: Case-1: Comparison of line flows in both systems.

Line no.	*S. Bus*	*R. Bus*	*Original system (Active)*	*Equivalent system (Active)*	*% Error*	*Original system (Reactive)*	*Equivalent system (Reactive)*	*% Error*
A	**15**	**16**	0.6387	0.8606	−−	−0.0958	−0.1217	−−
1	1	2	0.1282	0.1250	0.41	−0.2544	−0.2548	0.15
2	1	3	−0.1403	−0.1409	0.01	0.2573	0.2570	0.11
3	1	5	0.4522	0.4540	0.39	−0.0502	−0.0504	0.39
4	2	4	0.2970	0.2974	0.13	0.2260	0.2259	0.04
5	2	6	0.3811	0.3810	0.01	−0.3295	−0.3293	0.06
6	3	9	0.1686	0.1696	0.58	−0.1689	−0.1690	0.05
7	3	24	−2.114	−2.1200	0.28	0.0895	0.0893	0.22
8	4	9	−0.4478	−0.4471	0.01	0.0904	0.0903	0.11
9	5	10	−0.2623	−0.2600	0.87	−0.1849	−0.1850	0.05
10	6	10	−0.9907	−0.9912	0.05	−0.6007	−0.6005	0.33
11	7	8	0.2500	0.2500	0.00	0.5050	0.5057	0.13
12	8	9	−0.7818	−0.7810	0.23	0.2579	0.2581	0.07
13	8	10	0.6832	0.6830	0.02	−0.1064	−0.1068	0.37
14	9	11	−1.3441	−1.3440	0.01	−0.1707	−0.1710	0.17
15	10	12	−1.5064	−1.5066	0.01	−0.0658	−0.0654	0.61
16	10	11	−1.8815	−1.8814	0.01	0.5436	0.5432	0.11
17	9	12	−2.048	-2.048	0.00	0.661	0.661	0.00
18	11	13	−1.6873	−1.6878	0.01	−0.0203	−0.0204	0.49
19	11	14	−1.5514	−1.5520	0.01	−0.0843	−0.0841	0.38
20	12	13	−1.3802	−1.3803	0.01	−0.2231	−0.2234	0.13
21	12	23	−2.1904	−2.1870	0.15	0.2367	0.2369	0.08
22	13	23	−1.7475	−1.7430	0.25	0.2734	0.2730	0.14
23	14	**16**	−3.5047	−3.5102	0.15	0.6622	0.6620	0.03
26	**15**	24	2.1591	2.1604	0.06	0.4796	0.4794	0.04
28	**16**	19	0.7186	0.7168	0.27	0.2555	0.2555	0.00
32D	19	20	−0.5466	−0.5387	1.44	−0.0421	−0.0420	0.23
33D	20	23	−1.1882	−1.1799	0.69	−0.1019	−0.1017	0.18

5.2.1 Case-2: Outage of Line no. 7

The load flow results of previous case (case-1) is obtained considering the availability of all components of the transmission facilities in the system i.e. the equivalent is compared with the original at base case operating point. To justify the equivalent model for cases other than the base case, the equivalent was tested for line outages in the area of interest of the two systems. FDLF results are tabulated when line no 7 is taken out from the original system. The percentage error is also calculated for the voltage, bus angle and the line flows. Line number 7 is a transformer link between bus number 24 and 3. With this transformer link out the southern part of the system will not be able to receive any power from bus number 15 which is a generator bus as line no. 23 cannot transmit power beyond its power carrying capability. Tables 5.7 and 5.8 show the results of load flow analysis for the two systems. The % age error between the systems are within the specified limits.

Table 5.7: Comparison of bus voltages and bus angles for Case-2.

Bus No.	*BusVoltage Original System p.u.*	*BusVoltage Equivalent System p.u.*	*% Error*	*BusAngle Original System deg.*	*BusAngle Equivalent System deg.*	*% Error*
1	1.0000	1.0000	0.00	−21.3461	−21.5364	0.88
2	1.0000	1.0000	0.00	−31.1735	−31.1789	0.01
3	0.8794	0.8794	0.00	−38.0725	−38.0740	0.00
4	0.9459	.9459	0.00	−31.9524	−31.8670	0.26
5	0.9877	0.9877	0.00	−31.5261	−31.6591	0.42
6	1.0328	1.0328	0.00	−33.0306	−33.1436	0.34
7	1.0000	1.0000	0.00	−35.6780	−35.5760	0.28
8	0.9562	0.9562	0.00	−35.9802	−35.9562	0.06
9	0.9384	0.9384	0.00	−27.8894	−27.8874	0.00
10	1.0033	1.0033	0.00	−28.2263	−28.5673	1.19
11	0.9741	0.9741	0.00	−16.5264	−16.5454	0.11
12	0.9638	0.9638	0.00	−16.3838	−16.3678	0.09
13	1.0000	1.0000	0.00	−11.5625	−11.5785	0.13
14	1.0000	1.0000	0.00	−9.8515	−9.6785	1.78
15	1.0000	1.0000	0.00	3.4057	3.5643	4.45
16	1.0000	1.0000	0.00	0.9985	0.9965	0.20
19	0.9915	0.9915	0.00	−1.1192	−1.1212	0.17
20	0.9948	0.9948	0.00	−0.9024	−0.9164	1.52
23	1.0000	1.0000	0.00	0.0000	0.0000	0.00
24	1.0028	1.0028	0.00	3.3847	3.3047	2.36

Table 5.8: Comparison of line flows for the two systems for Case-2

Line no.	*S. Bus*	*R. Bus*	*Original system (Active)*	*Equivalent system (Active)*	*% Error*	*Original system (Reactive)*	*Equivalent system (Reactive)*	*% Error*
A	**15**	**16**	2.3964	3.0348	−−	−0.2719	−0.3360	−−
1	1	2	−0.2283	−0.2286	0.13	−0.1875	−0.1865	0.53
2	1	3	0.6016	0.6019	0.04	0.4155	0.4145	0.24
3	1	5	0.0668	0.0666	0.30	0.1172	0.1160	1.02
4	2	4	0.1989	0.1978	0.55	0.3589	0.3586	0.08
5	2	6	0.1226	0.1224	0.16	−0.2259	−0.2258	0.04
6	3	9	−1.2288	−1.2278	0.08	−0.0214	−0.0212	0.93
7	3	24	*out*	*out*	−−	*out*	*out*	−−
8	4	9	−0.5470	−0.5468	0.03	0.2186	0.2184	0.09
9	5	10	−0.6437	−0.6435	0.03	0.0157	0.0157	0.00
10	6	10	−1.2401	−1.2401	0.00	−0.4626	−0.4626	0.00
11	8	7	0.2500	0.2500	0.00	0.6399	0.6399	0.00
12	8	9	−0.6792	−0.6791	0.01	0.3125	0.3124	0.03
13	8	10	−0.7884	−0.7881	0.03	−0.0361	−0.0363	0.55
14	9	11	−2.1510	−2.1500	0.04	−0.1262	−0.1261	0.07
15	10	12	−2.3450	−2.3449	0.00	0.7819	0.7817	0.01
16	10	11	−2.3452	−2.3451	0.00	0.6561	0.6559	0.03
17	9	12	−2.1515	−2.1513	0.00	−0.0085	−0.0084	1.17
18	11	13	−1.8000	−1.8000	0.00	−0.2702	−0.2701	0.03
19	11	14	−2.7219	−2.7217	0.00	−0.1358	−0.1356	0.14
20	12	13	−1.7583	−1.7581	0.00	−0.4814	−0.4811	0.06
21	12	23	−2.7642	−2.7642	0.00	0.3053	0.3053	0.00
22	13	23	−2.2509	−2.2505	0.00	0.4327	0.4324	0.06
23	14	**16**	−4.7041	−4.7040	0.00	1.0237	1.0236	0.00
26	**15**	24	0.0000	0.0000	0.00	−0.1092	−0.1092	0.00
28	**16**	19	1.6113	1.6111	0.00	0.1649	0.1647	0.12
32D	19	20	−0.1033	−0.1033	0.00	−0.1110	−0.1110	0.00
33D	20	23	−0.7434	−0.7431	0.04	−0.1594	−0.1591	0.18

5.2.2 Case-3: Outage of Line no. 23

Fast decoupled load flow is conducted for the original system and equivalent system when line number 23 is taken out from the system. Line number 23 is a line which connects the area of interest with the boundary bus. The outage of any boundary line is considered to have most severe effect on the system. The results of the load flow analysis are shown in Tables 5.9 and 5.10. Comparison of both systems gives confidance to the proposed equivalencing algorithm s the % age error between the results of both the systems are lower then the specified limits.

Table 5.9: Comparison of bus voltages and bus angles for case-3.

Bus No.	*BusVoltage Orig.System p.u.*	*BusVoltage Eq.System p.u.*	*% Error*	*BusAngle Orig.System deg.*	*BusAngle Eq.System deg.*	*% Error*
1	1.0000	1.0000	0.00	−29.6927	−29.6927	0.00
2	1.0000	1.0000	0.00	−29.9294	−29.8122	0.33
3	0.9223	0.9223	0.00	−21.8381	−21.7865	0.23
4	0.9507	0.9507	0.00	−31.9887	−31.8765	0.35
5	0.9895	0.9895	0.00	−32.7161	−32.6754	0.12
6	1.0352	1.0352	0.00	−35.9055	−35.8676	0.11
7	1.0000	1.0000	0.00	−38.2618	−38.1234	0.48
8	0.9586	0.9586	0.00	−38.6005	−38.5768	0.06
9	0.9463	0.9463	0.00	−29.0923	−29.1456	0.18
10	1.0067	1.0067	0.00	−32.4018	−32.3678	0.09
11	0.9842	0.9842	0.00	−26.9490	−26.9678	0.06
12	0.9649	0.9649	0.00	−19.7287	−19.7287	0.00
13	1.0000	1.0000	0.00	−17.0335	−17.0456	0.07
14	1.0000	1.0000	0.00	−31.8994	−31.8567	0.13
15	1.0000	1.0000	0.00	5.7854	5.7843	0.01
16	1.0000	1.0000	0.00	6.0203	6.0345	0.23
19	0.9899	0.9899	0.00	1.7408	1.7267	0.81
20	0.9942	0.9942	0.00	0.1003	0.1000	0.29
23	1.0000	1.0000	0.00	0.0000	0.0000	0.00
24	0.9350	0.9350	0.00	−4.0797	−4.0564	0.57

Table 5.10: Comparison of line flows of two systems for Case-3

Line no.	*S. Bus*	*R. Bus*	*Original system (Active)*	*Equivalent system (Active)*	*% Error*	*Original system (Reactive)*	*Equivalent system (Reactive)*	*% Error*
A	**15**	**16**	−0.2332	−0.2181	−−	0.0119	0.0097	−−
1	1	2	0.2874	0.2865	0.31	−0.2837	−0.2828	0.31
2	1	3	−0.4606	−0.4612	0.13	0.4993	0.4986	0.14
3	1	5	0.6134	0.6128	0.09	−0.0286	−0.0267	6.64
4	2	4	0.3483	0.3480	0.07	0.2863	0.2845	0.62
5	2	6	0.4889	0.4887	0.04	−0.3066	−0.3060	0.19
6	3	9	0.8375	0.8373	0.02	−0.3578	−0.3576	0.05
7	3	24	−3.1243	−3.1246	0.00	0.4364	0.4366	0.04
8	4	9	−0.3986	−0.3983	0.07	0.1419	0.1415	0.28
9	5	10	−0.1048	−0.1045	0.28	−0.1777	−0.1774	0.16
10	6	10	−0.8868	−0.8866	0.02	−0.5937	−0.5935	0.03
11	7	8	0.2501	0.2500	0.03	0.6010	0.6005	0.08
12	8	9	−0.8155	−0.8145	0.12	0.3373	0.3367	0.17
13	8	10	−0.6512	−0.6534	0.33	−0.0970	−0.0969	0.10
14	9	11	−0.4265	−0.4257	0.18	−0.4073	−0.4063	0.24
15	10	12	−2.5175	−2.5165	0.03	0.8531	0.8529	0.02
16	10	11	−1.1129	−1.1120	0.08	0.3543	0.3535	0.33
17	9	12	−1.7718	−1.7718	0.00	−0.0154	−0.0151	1.9
18	11	13	−3.5065	−3.5065	0.00	0.3826	0.3824	0.05
19	11	14	1.9630	1.9630	0.00	−0.5811	−0.5810	0.01
20	12	13	−1.0251	−1.0250	0.00	−0.6048	−0.6048	0.00
21	12	23	−3.2885	−3.2882	0.00	0.5635	0.5633	0.03
22	13	23	−3.2688	−3.2634	0.16	0.8361	0.8359	0.02
23	14	**16**	*out*	*out*	−−	*out*	*out*	−−
26	**15**	24	3.2301	3.2300	0.00	1.0474	1.0470	0.03
28	**16**	19	3.2170	3.2165	0.01	0.1132	0.1130	0.01
32D	19	20	0.6880	0.6880	0.00	−0.2261	−0.2261	0.00
33D	20	23	0.0453	0.0450	0.66	−0.2947	−0.2943	0.13

5.2.3 Case-4: Outage of Line 28

Line number 28 is another boundary line which connects the boundary bus number 16 with a load bus (bus number 19). The load flow is conducted for both systems i.e. the original system and the equivalent system. This type of comparative analysis was conducted for all the line outages in the area of interest but the result of only those cases which have the most severe impact on the system are reported. The validity of the equivalent model can be observed from the percentage error shown in tables 5.11 and 5.12.

Table 5.11: Comparison of bus voltages and bus angles for Case-4.

Bus No.	*BusVoltage Orig.System p.u.*	*BusVoltage Eq.System p.u.*	*% Error*	*BusAngle Orig.System deg.*	*BusAngle Eq.System deg.*	*% Error*
1	1.0000	1.0000	0.00	−18.6605	−18.6584	0.01
2	1.0000	1.0000	0.00	−18.7888	−18.1824	3.2
3	0.9464	0.9463	0.01	−15.1133	−14.8559	1.7
4	0.9598	0.9598	0.00	−20.6265	−20.0365	2.8
5	0.9945	0.9946	0.01	−21.0617	−21.1056	0.20
6	1.0437	1.0437	0.00	−23.8550	−23.6553	0.84
7	1.0000	1.0000	0.00	−26.0106	−26.0543	0.16
8	0.9647	0.9647	0.00	−26.4394	−26.1254	1.30
9	0.9625	0.9625	0.00	−17.6323	−17.0530	3.21
10	1.0166	1.0165	0.00	−20.1286	−19.5844.	2.74
11	0.9871	0.9871	0.00	−10.6050	−10.6055	0.18
12	0.9836	0.9837	0.01	−10.8156	−10.8125	0.02
13	1.0000	1.0000	0.00	−6.9996	−6.9989	0.01
14	1.0000	1.0000	0.00	−5.5962	−5.6089	0.22
15	1.0000	1.0000	0.0	4.1346	4.1356	0.02
16	1.0000	1.0000	0.00	3.6424	3.6563	0.38
19	0.9783	0.9783	0.00	−3.9876	−3.9730	0.36
20	0.9896	0.9896	0.00	−1.9089	−1.8969	0.62
23	1.0000	1.0000	0.00	0.0000	0.0000	0.00
24	0.9605	0.9596	0.09	−2.8944	−2.0098	2.92

Table 5.12: Comparison of line flows of the two systems for Case-4.

Line no.	*S. Bus*	*R. Bus*	*Original system (Active)*	*Equivalent system (Active)*	*% Error*	*Original system (Reactive)*	*Equivalent system (Reactive)*	*% Error*
A	**15**	**16**	0.4891	0.4891	−−	−0.0783	−0.0783	−−
1	1	2	0.1558	0.1560	0.12	−0.2595	−0.2678	3.01
2	1	3	−0.1964	−0.1970	0.30	0.2845	0.2756	5.8
3	1	5	0.4807	0.4809	0.04	−0.0604	−0.0614	1.62
4	2	4	0.3056	0.3060	0.13	0.2247	0.2254	0.31
5	2	6	0.4000	0.4012	0.30	−0.3357	−0.3356	0.31
6	3	9	0.2862	0.2870	0.27	−0.2088	−0.2086	0.09
7	3	24	−2.2900	−2.2902	0.00	0.1490	0.1495	0.46
8	4	9	−0.4393	−0.4395	0.04	0.0884	0.0897	1.50
9	5	10	−0.2344	−0.2354	0.42	−0.1974	−0.1984	0.50
10	6	10	−0.9727	−0.9737	0.10	−0.6104	−0.6104	0.00
11	7	8	0.2500	0.2500	0.00	0.5030	0.5041	0.21
12	8	9	−0.7881	−0.7879	0.02	0.2622	0.2631	0.34
13	8	10	−0.6769	−0.6770	0.01	−0.1127	−0.1134	0.32
14	9	11	−1.3902	−1.3912	0.07	−0.1590	−0.1585	0.31
15	10	12	−1.9125	−1.9130	0.02	0.6090	0.6087	0.04
16	10	11	−1.9637	−1.9638	0.00	0.5757	0.5760	0.05
17	9	12	−1.3432	−1.3435	0.02	−0.1253	−0.1253	0.00
18	11	13	−1.3121	−1.3129	0.06	−0.1078	−0.1080	0.18
19	11	14	−2.0560	−2.0562	0.00	0.0075	0.0080	6.25
20	12	13	−1.3905	−1.3911	0.04	−0.1641	−0.1641	0.00
21	12	23	−1.8786	−1.8788	0.01	0.1565	0.1571	0.38
22	13	23	−1.3757	−1.3758	0.00	0.1719	0.1720	0.05
23	14	**16**	−4.0195	−4.0180	0.03	0.8095	0.8093	0.04
26	**15**	24	2.3428	2.3430	0.00	0.5427	0.5429	0.03
28	**16**	19	*out*	*out*	−−	*out*	*out*	−−
32D	19	20	−0.9050	−0.9059	0.09	−0.1870	−0.1872	0.10
33D	20	23	−1.5495	−1.5489	0.03	−0.2711	−0.2707	0.14

5.2.4 Case-5: Outage of Lines 2 and 26

Load flow analysis result is shown in Tables 5.13 and 5.14. Error in bus voltages and line flows between the original system and the equivalent sytem is very small. In this case, line 2 and line 26 are taken out from the original system and the equivalent system.

Table 5.13: Comparison of bus voltages and angles for case-5

Bus No.	*BusVoltage Orig.System p.u.*	*BusVoltage Eq.System p.u.*	*% Error*	*BusAngle Orig.System deg.*	*BusAngle Eq.System deg.*	*% Error*
01	1.0000	1.0000	0.00	−29.7582	−29.7687	0.03
2	1.0000	1.0000	0.00	−29.9056	−29.8757	0.09
3	0.6962	0.6968	0.06	−49.2262	−49.6547	0.86
4	0.9172	0.9175	0.03	−32.6655	−32.5768	0.27
5	0.9822	0.9822	0.00	−30.8595	−30.6874	0.56
6	1.0231	1.0237	0.00	−32.9903	−32.7658	0.68
7	1.0000	1.0000	0.00	−37.7883	−37.6874	0.26
8	0.9416	0.9412	0.04	−37.8657	−37.5874	0.73
9	0.8870	0.8870	0.00	−30.0434	−30.6579	2.00
10	0.9916	0.9918	0.02	−28.4901	−28.8737	1.34
11	0.9621	0.9623	0.02	−16.9530	−16.6986	1.56
12	0.9486	0.9486	0.00	−16.7928	−16.4875	1.81
13	1.0000	1.0000	0.00	−11.9180	−11.4769	3.71
14	1.0000	1.0000	0.00	−10.1530	−10.1647	0.11
15	1.0000	1.0000	0.00	3.2301	3.27654	1.41
16	1.0000	1.0000	0.00	0.8230	0.8276	0.55
19	0.9915	0.9915	0.00	−1.2193	−1.2578	3.06
20	0.9948	0.9948	0.00	−0.9375	−0.9365	0.10
23	1.0000	1.0000	0.00	0.0000	0.0000	0.00
24	0.6962	0.6965	0.04	−49.2262	−49.5784	0.71

Table 5.14: Comparison of the line flows for two systems foe case-5

Line no.	*S. Bus*	*R. Bus*	*Original system (Active)*	*Equivalent system (Active)*	*% Error*	*Original system (Reactive)*	*Equivalent system (Reactive)*	*% Error*
A	**15**	**16**	2.3965	3.0348	−−	−0.2719	−0.3360	−−
1	1	2	0.1789	0.1789	0.00	−0.2638	−0.2640	0.07
2	1	3	*out*	*out*	−−	*out*	*out*	−−
3	1	5	0.2611	0.2613	0.07	0.1342	0.1349	0.51
4	2	4	0.4874	0.4873	0.01	0.5186	0.5189	0.22
5	2	6	0.2415	0.2419	0.07	−0.2012	−0.2019	0.34
6	3	9	−1.7993	−1.7995	0.00	−0.3699	−0.3712	0.35
7	3	24	0.0000	0.0000	0.00	0.00	0.0000	0.00
8	4	9	−0.2698	−0.2699	0.07	0.3337	0.3341	0.11
9	5	10	−0.4509	−0.4512	0.01	0.0092	0.0095	3.15
10	6	10	−1.1229	−1.1232	0.91	−0.4450	−0.4452	0.04
11	7	8	0.2501	0.2512	0.43	0.8773	0.8773	0.00
12	8	9	−0.5586	−0.5586	0.00	0.4837	0.4841	0.08
13	8	10	−0.9147	−0.9149	0.02	0.0073	0.0076	3.94
14	9	11	−2.3173	−2.3178	0.01	−0.4665	−0.4671	0.10
15	10	12	−2.2520	−2.2525	0.01	0.8033	0.8041	0.08
16	10	11	−2.2577	−2.2579	0.01	0.6408	0.6412	0.24
17	9	12	−2.3083	−2.3085	0.01	−0.3213	−0.3213	0.00
18	11	13	−1.8327	−1.8329	0.01	−0.4991	−0.4981	0.01
19	11	14	−2.7718	−2.7713	0.00	−0.3926	−0.3936	0.25
20	12	13	−1.7869	−1.7871	0.01	−0.7680	−0.7690	0.13
21	12	23	−2.8030	−2.8033	0.00	0.1829	0.1831	0.10
22	13	23	−2.3182	−2.3186	0.01	0.4560	0.4557	0.06
23	14	**16**	−4.7574	−4.7574	0.00	1.0412	1.0418	0.05
26	**15**	24	*out*	*out*	−−	*out*	*out*	−−
28	**16**	19	1.5553	1.5557	0.01	0.1692	0.1697	0.29
32D	19	20	−0.1310	−0.1313	0.15	−0.1067	−0.1072	0.29
33D	20	23	−0.7711	−0.7715	0.05	−0.1554	−0.1549	0.32

5.3 Study System-B

In this study case, the external system with buses 17,18,19,20,21 and 22 (6 buses) are reduced by using the same approach as given in chapter-3. Boundary buses are 15, 16 and 23 and the rest is the area of interest. After equivalencing, the system reduces to 18 buses and load flow comparison is conducted for the area of interest.The external, boundary and area of interest are shown in fig 5.4. The reduced system is shown in Figure 5.5 The equivalent probabilistic boundary line, generation and load model are calculated in the same manner as described in the previous section.These models are represented at the boundary buses.

The fast decoupled load flow analysis is carried out for the full system and for the reduced system. The comparison was conducted for the reference case when all the transmission facilities are assumed to be available. Then outages in the area of interest are applied. The load flow comparison is given in the next sections which validates the equivalent with respect to load flow point.

5.3.1 Case-6: Reference case

In this case, all the transmission facilities are considered to be available. Fast Decoupled Load Flow solution technique was applied for the solution of the network. The load flow results is obtained, tables 5.15 and 5.16, show the results of the load flow analysis . The accuracy of the equivalent can be judged by the % age error

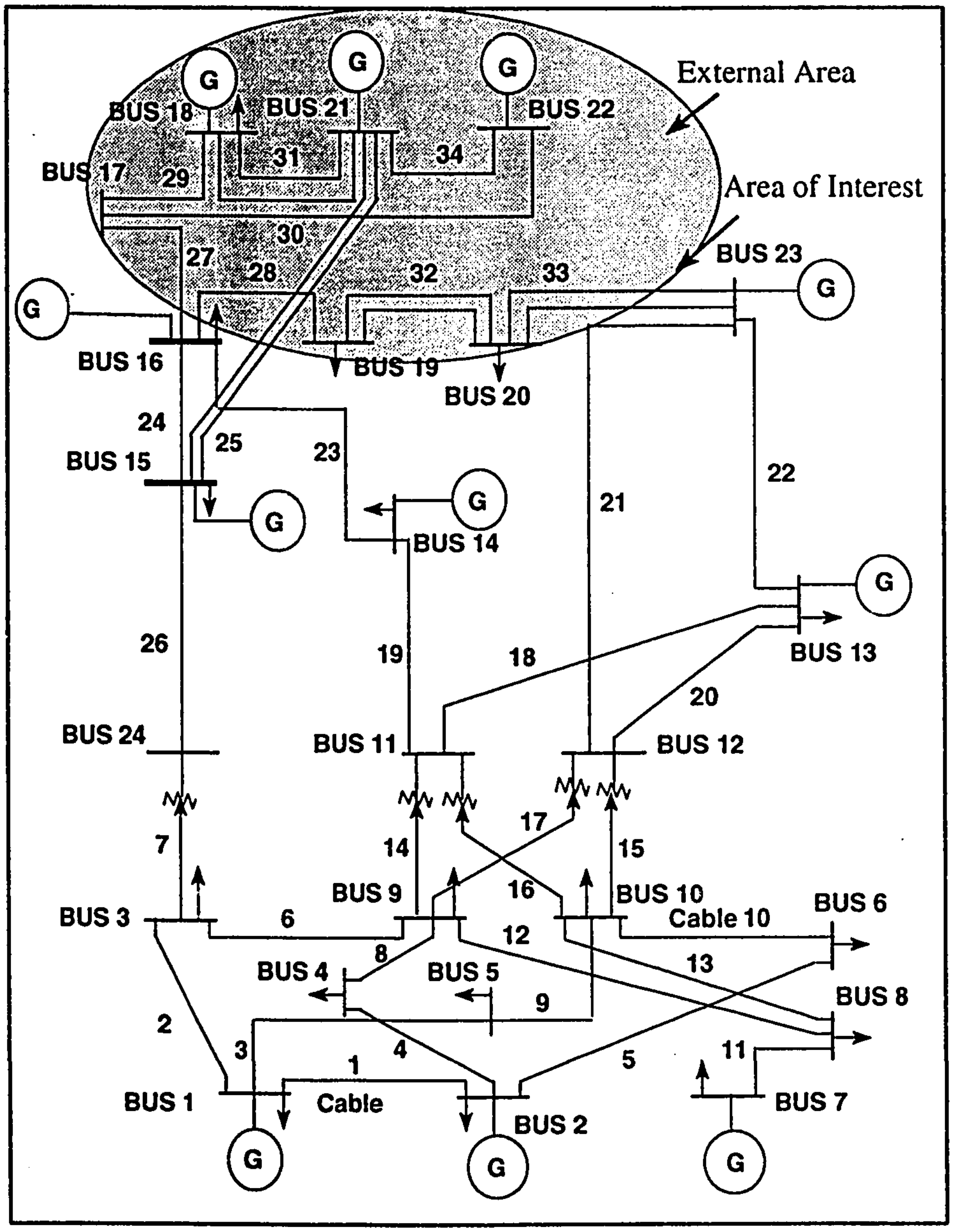

Figure 5.4: Study System B

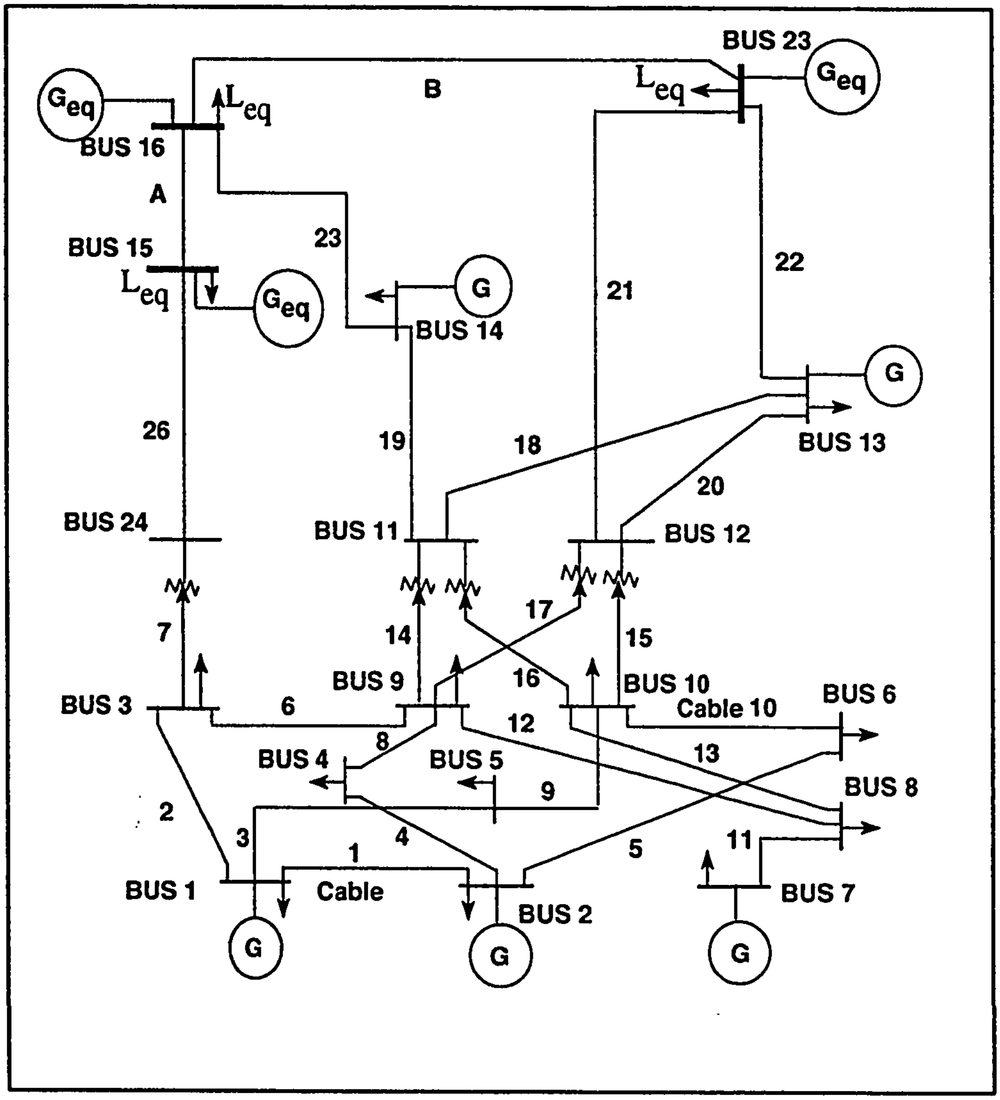

Figure 5.5: Equivalent of IEEE-RTS 24 Bus Study System-B

between the results of a full system and its equivalent model. B is a fictitious line between bus 16 and bus 23 which is obtained after the reduction process.

Table 5.15: Comparison of the bus voltages and the bus angles for case-6.

Bus No.	*BusVoltage Orig.System p.u.*	*BusVoltage Eq.System p.u.*	*% Error*	*BusAngle Orig.System deg.*	*BusAngle Eq.System deg.*	*% Error*
1	1.0000	1.0000	0.00	−21.5594	−21.5694	0.04
2	1.0000	1.0000	0.00	−21.6649	−21.6701	0.02
3	0.9484	0.9483	0.01	−18.8260	−18.8224	0.01
4	0.9599	0.9592	0.07	−23.4347	−23.4353	0.01
5	0.9942	0.9947	0.05	−23.8098	−23.8102	0.00
6	1.0431	1.0435	0.01	−26.5165	−26.5181	0.02
7	1.0000	1.0000	0.00	−28.6866	−28.6871	0.01
8	0.9645	0.9643	0.02	−29.1135	−29.1139	0.00
9	0.9626	0.9628	0.02	−20.3835	−20.3841	0.02
10	1.0158	1.0153	0.04	−22.7199	−22.7129	0.03
11	0.9876	0.9879	0.01	−13.5979	−13.5960	0.02
12	0.9807	0.9803	0.04	−12.7021	−12.7013	0.02
13	1.0000	1.0000	0.00	−8.9252	−8.9257	0.01
14	1.0000	1.0000	0.00	−9.8476	−9.8496	0.01
15	1.0000	1.0000	0.00	−1.1691	−1.1671	0.05
16	1.0000	1.0000	0.00	−1.8117	−1.8137	0.11
23	1.0000	1.0000	0.00	0.0000	0.0000	0.00
24	0.9639	0.9632	0.06	−7.6280	−7.6380	0.13

Table 5.16: Comparison of the line flows for the two systems for Case-6

Line no.	*S. Bus*	*R. Bus*	*Original system (Active)*	*Equivalent system (Active)*	*% Error*	*Original system (Reactive)*	*Equivalent system (Reactive)*	*% Error*
A	**15**	**16**	0.6387	0.8558	−−	−0.0958	−0.1176	−−
B	**16**	**23**	−−	0.4686	−−	−−	−0.1089	−−
1	1	2	0.1282	0.1289	0.05	−0.2544	−0.2598	2.07
2	1	3	−0.1403	−0.1405	0.01	0.2573	0.2569	0.15
3	1	5	0.4522	0.4525	0.06	−0.0502	−0.0512	1.94
4	2	4	0.2970	0.2972	0.13	0.2260	0.2253	0.30
5	2	6	0.3811	0.3816	0.17	−0.3295	−0.3287	0.29
6	3	9	0.1686	0.1689	0.02	−0.1689	−0.1712	1.34
7	3	24	−2.1144	−2.1149	0.00	0.0895	0.0865	3.35
8	4	9	−0.4478	−0.4478	0.01	0.0904	0.0918	1.52
9	5	10	−0.2623	−0.2621	0.04	−0.1849	−0.1857	0.48
10	6	10	−0.9907	−0.9903	0.11	−0.6007	−0.6009	0.03
11	7	8	0.2500	0.2503	0.03	0.5050	0.5059	0.17
12	8	9	−0.7818	−0.7815	0.03	0.2579	0.2581	0.07
13	8	10	−0.6832	−0.6832	0.00	−0.1064	−0.1071	0.65
14	9	11	−1.3441	−1.3449	0.05	−0.1707	−0.1713	0.35
15	10	12	−2.0482	−2.0489	0.03	0.6612	0.6619	0.10
16	10	11	−1.8815	−1.8812	0.02	0.5436	0.5441	0.09
17	9	12	−1.5064	−1.5069	0.01	−0.0658	−0.0662	0.60
18	11	13	−1.6873	−1.6878	0.02	−0.0203	−0.0212	3.3
19	11	14	−1.5514	−1.5517	0.01	−0.0843	−0.0851	0.94
20	12	13	−1.3802	−1.3805	0.01	−0.2231	−0.2243	0.40
21	12	23	−2.1904	−2.1909	0.01	0.2367	0.2374	0.29
22	13	23	−1.7475	−1.7479	0.02	0.2734	0.2741	0.29
23	14	**16**	−3.5047	−3.5047	0.01	0.6622	0.6631	0.13
26	**15**	24	2.1591	2.1596	0.01	0.4796	0.4798	0.04

5.3.2 Case-7: Outage of Line no. 21

Tables 5.17 and 5.18 show the load flow analysis results for the two systems. Percentage error between original system and the equivalent system is very small which gives confidence to the equivalencing algorithm.

Table 5.17: Comparison of bus voltages and bus angles of the two systems for Case-7.

Bus No.	*BusVoltage Orig.System p.u.*	*BusVoltage Eq.System p.u.*	*% Error*	*BusAngle Orig.System deg.*	*BusAngle Eq.System deg.*	*% Error*
1	1.0000	1.0000	0.00	−29.3332	−29.4535	0.40
2	1.0000	1.0000	0.00	−29.4784	−29.6354	0.68
3	0.9433	0.9433	0.00	−25.1467	−25.2953	0.60
4	0.9579	0.9579	0.00	−31.3419	−31.5342	0.64
5	0.9931	0.9931	0.00	−31.8242	−31.6453	0.91
6	1.0413	1.0413	0.00	−34.6782	−34.6342	0.01
7	1.0000	1.0000	0.00	−36.8821	−36.7353	0.39
8	0.9632	0.9632	0.00	−37.2896	−37.3564	0.17
9	0.9591	0.9596	0.05	−28.3503	−28.4322	0.28
10	1.0137	1.0132	0.05	−30.9763	−30.8735	0.33
11	0.9835	0.9833	0.02	−20.1180	−20.3242	1.01
12	0.9801	0.9807	0.06	−23.0665	−23.3242	1.09
13	1.0000	1.0000	0.00	−15.6064	−15.3252	1.80
14	1.0000	1.0000	0.00	−14.7060	−14.5364	0.10
15	1.0000	1.0000	0.00	−14.7060	−14.7123	0.04
16	1.0000	1.0000	0.00	−4.6923	−4.6787	0.28
23	1.0000	1.0000	0.00	0.0000	0.0000	0.00
24	0.9572	0.9574	0.02	−12.1413	−12.1736	0.26

Table 5.18: Comparison of line flows of two systems for Case-7.

Line no.	*S. Bus*	*R. Bus*	*Original system (Active)*	*Equivalent system (Active)*	*% Error*	*Original system (Reactive)*	*Equivalent system (Reactive)*	*% Error*
A	**15**	**16**	0.3642	0.5407	−−	0.0143	0.0822	−−
B	**16**	**23**	−−	1.5024	−−	−−	−0.1860	−−
1	1	2	0.1763	0.1761	0.11	−0.2633	−0.2654	0.79
2	1	3	−0.2377	−0.2374	0.12	0.3135	0.3135	0.00
3	1	5	0.5015	0.5016	0.01	−0.0482	−0.0482	0.00
4	2	4	0.3121	0.3123	0.02	0.2382	0.2343	1.73
5	2	6	0.4141	0.4140	0.02	−0.3258	−0.3256	0.06
6	3	9	0.3708	0.3703	0.13	−0.2237	−0.2238	0.04
7	3	24	−2.4178	−2.4174	0.01	0.1853	0.1857	0.21
8	4	9	−0.4332	−0.4331	0.02	0.1006	0.1012	0.59
9	5	10	−0.2140	−0.2140	0.00	−0.1868	−0.1866	0.11
10	6	10	−0.9589	−0.9586	0.03	−0.6017	−0.6019	0.12
11	7	8	0.2500	0.2500	0.00	0.5262	0.5267	0.13
12	8	9	−0.7929	−0.7927	0.02	0.2767	0.2764	0.11
13	8	10	−0.6725	−0.6722	0.04	−0.1054	−0.1045	0.86
14	9	11	−1.6137	−1.6131	0.03	−0.1192	−0.1186	0.50
15	10	12	−1.6149	−1.6134	0.09	0.5624	0.5618	0.10
16	10	11	−2.2219	−2.2207	0.05	0.6387	0.6376	0.17
17	9	12	−0.1192	−0.1189	0.25	−0.1650	−0.1648	0.12
18	11	13	−1.6345	−1.6345	0.00	−0.1157	−0.1147	0.86
19	11	14	−2.2196	−2.2197	0.00	−0.0391	−0.0389	0.76
20	12	13	−2.6609	−2.6608	0.00	0.0587	0.0576	2.38
21	12	23	*out*	*out*	−−	*out*	*out*	−−
22	13	23	−3.0071	−3.0068	0.01	0.7215	0.7210	0.06
23	14	**16**	−4.1870	−4.1770	0.23	0.8599	0.8612	0.15
26	**15**	24	2.4773	2.4769	0.01	0.6052	0.6050	0.03

5.3.3 Case-8: Outage of Lines 7 and 20

Tables 5.19 and 5.20 shows the comparison of the original system and its equivalent with respect to load flow analysis. The error between both results is quite small. Load flow analysis is conducted while lines 7 & 20 are out from both the systems.

Table 5.19: Comparison of bus voltages and bus angles for two systems for case-8.

Bus No.	*BusVoltage Orig.System p.u.*	*BusVoltage Eq.System p.u.*	*% Error*	*BusAngle Orig.System deg.*	*BusAngle Eq.System deg.*	*% Error*
1	1.0000	1.0000	0.00	−34.9706	−34.9526	0.01
2	1.0000	1.0000	0.00	−34.7795	−34.4765	0.86
3	0.8639	0.8627	0.02	−41.6772	−41.6753	0.00
4	0.9339	0.9337	0.02	−35.3750	−35.6453	0.60
5	0.9774	0.9774	0.00	−34.9504	−34.6475	0.75
6	1.0157	1.0146	0.02	−36.3828	−36.5436	0.32
7	1.0000	1.0000	0.00	−39.4064	−39.5673	0.40
8	0.9467	0.9462	0.05	−39.5622	−39.5754	0.02
9	0.9174	0.9170	0.04	−30.9940	−30.6744	1.2
10	0.9828	0.9821	0.04	−31.3483	−31.3464	0.00
11	0.9590	0.9594	0.04	−16.3249	−16.3263	0.00
12	0.9264	0.9262	0.02	−21.6096	−21.6537	0.23
13	1.0000	1.0000	0.00	−8.1608	−8.5342	0.82
14	1.0000	1.0000	0.00	−9.7195	−9.4373	2.8
15	1.0000	1.0000	0.00	3.4825	3.2673	0.57
16	1.0000	1.0000	0.00	1.0754	1.1746	0.01
23	1.0000	1.0000	0.00	0.0000	0.0000	0.00
24	1.0028	1.0024	0.04	3.4615	3.4536	0.05

Table 5.20: Comparison of line flows of two systems for Case-8.

Line no.	*S. Bus*	*R. Bus*	*Original system (Active)*	*Equivalent system (Active)*	*% Error*	*Original system (Reactive)*	*Equivalent system (Reactive)*	*% Error*
A	**15**	**16**	2.981	3.0300	−−	−0.2874	−0.3234	−−
B	**16**	**23**	−−	0.4601	−−	−−	0.1080	−−
1	1	2	−0.2319	−0.2311	0.08	−0.1868	−0.1857	0.58
2	1	3	0.6109	0.6106	0.04	0.4861	0.4858	0.06
3	1	5	0.0610	0.0620	1.61	0.2407	0.2404	0.12
4	2	4	0.1985	0.1978	0.40	0.4534	0.4528	0.13
5	2	6	0.1195	0.1185	0.84	−0.1364	−0.1358	0.43
6	3	9	−1.2239	−1.2220	0.15	0.0314	0.0310	1.27
7	3	24	*out*	*out*	−−	*out*	*out*	−−
8	4	9	−0.5501	−0.5508	0.12	0.3025	0.3018	0.23
9	5	10	−0.6505	−0.6526	0.36	0.1174	0.1174	0.00
10	6	10	−1.2418	−1.2427	0.07	−0.3686	−0.3678	0.12
11	7	8	0.2500	0.2508	0.31	0.7952	0.7956	0.00
12	8	9	−0.6800	−0.6808	0.11	0.3824	0.3821	0.07
13	8	10	−0.7912	−0.7927	0.18	0.0352	0.0356	1.12
14	9	11	−2.6578	−2.6576	0.75	−0.0399	−0.0389	0.75
15	10	12	−1.8126	−1.8124	0.01	0.8677	0.8656	0.14
16	10	11	−2.8929	−2.8925	0.01	0.7427	0.7478	0.68
17	9	12	−1.6501	−1.6500	0.00	0.0830	0.0839	0.1.07
18	11	13	−2.8944	−2.8947	0.01	−0.2962	−0.2968	0.20
19	11	14	−2.6970	−2.6967	0.01	−0.4797	−0.4794	0.06
20	12	13	*out*	*out*	−−	*out*	*out*	−−
21	12	23	−3.4798	−3.4789	0.02	0.3282	0.3286	0.12
22	13	23	−1.6003	−1.6001	0.01	0.2316	0.2356	0.16
23	14	**16**	−4.6808	−4.6834	0.05	1.0160	1.0168	0.06
26	**15**	24	0.0000	0.0000	0.00	−0.1092	−0.1087	0.45

5.4 Study System-C: Replication of RTS systems

The aim of this section is the same as that of previous section. However, the IEEE RTS is comparatively small. For this reason and in order to show the applicability of the proposed equivalent technique to larger system sizes, the dimension of the original RTS is duplicated (Appendix A). The duplication is done as follows: each individual RTS of study system-C is identical, each individual RTS is linked by three lines. The single line diagram is shown in Figure 5.6 . The area of interest is defined as a full size RTS. Figure 5.7 shows the equivalent system. Several load flow analysis are conducted and are described in the following sections. This case is termed as case-9. Load flow comparison between the two systems (original system and equivalent system) are given in the following sections. Line outages are considered in the area of interest to validate the equivalent model for cases other than the base case. % age error between load flow results of the original system and the equivalent system is quite small which gives confidance in the equivalencing algorithm proposed in the thesis.

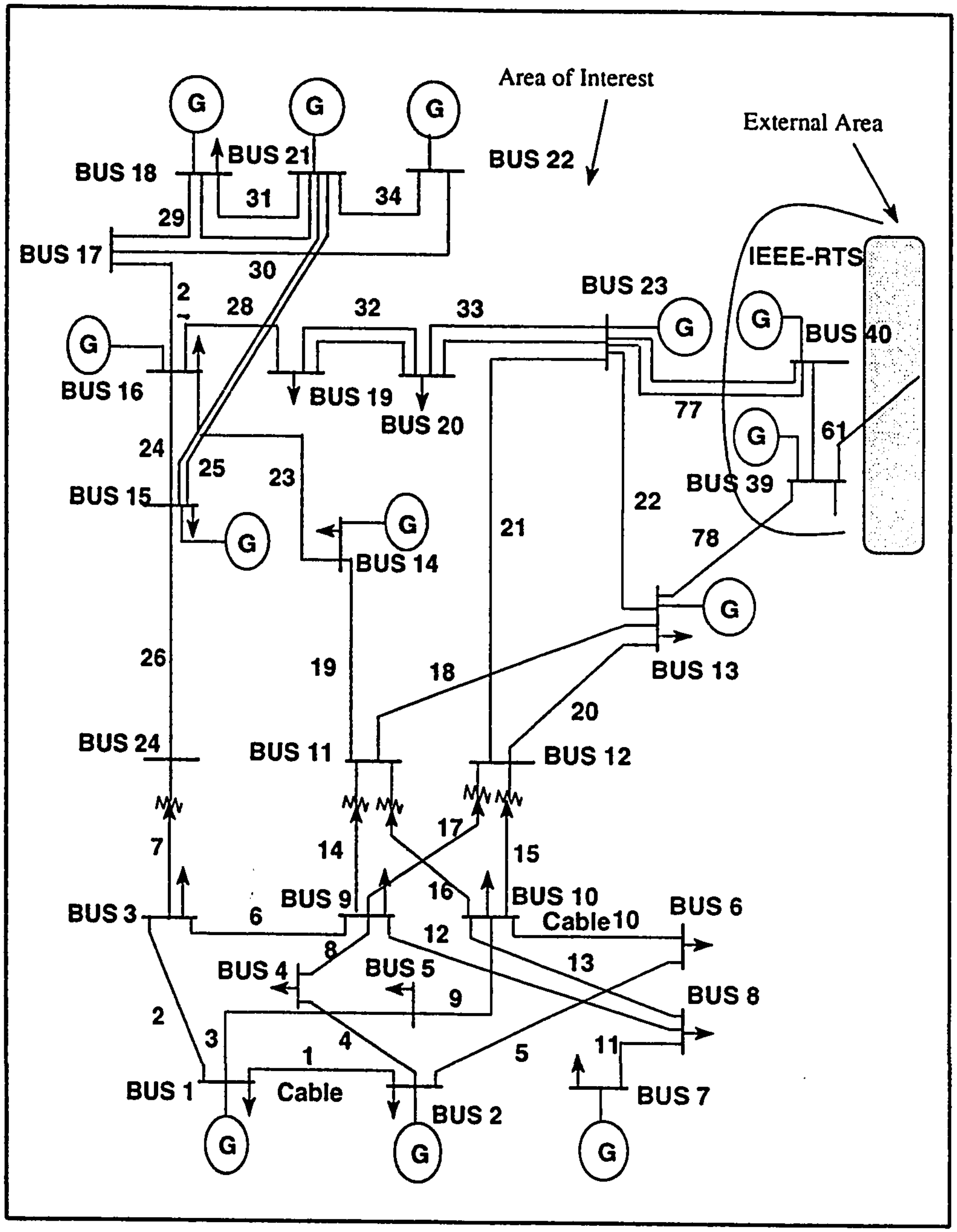

Figure 5.6: The single line diagram for two interconnected IEEE-RTS(Original system).

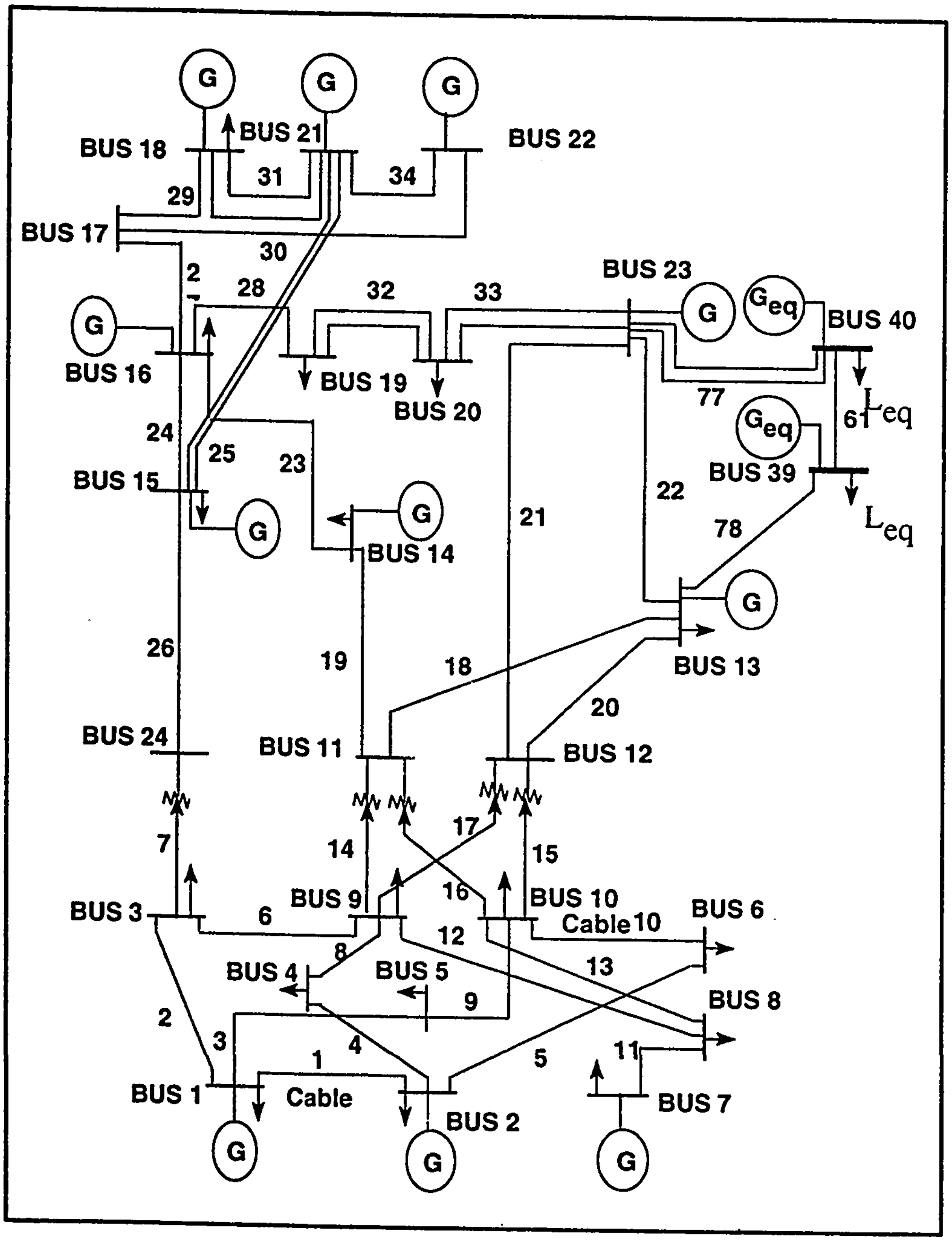

Figure 5.7: The single line diagram for two interconnected IEEE-RTS(Equivalent system).

Table 5.21: Comparison of bus voltages and bus angles for Case-9.

Bus No.	*BusVoltage Orig.System p.u.*	*BusVoltage Eq.System p.u.*	*% Error*	*BusAngle Orig.System deg.*	*BusAngle Eq.System deg.*	*% Error*
1	1.0000	1.0000	0.00	−23.0850	−23.6575	2.40
2	1.0000	1.0000	0.00	−23.1972	−23.1987	0.65
3	0.9476	0.9472	0.04	−20.1123	−20.5464	2.1
4	0.9595	0.9596	0.01	−24.9822	−24.7564	0.90
5	0.9940	0.9938	0.02	−25.3753	−25.6585	1.10
6	1.0427	1.0430	0.02	−28.1066	−28.6453	1.80
7	1.0000	1.0000	0.00	−30.2830	−30.5476	0.86
8	0.9643	0.9639	0.04	−30.7063	−30.5637	0.46
9	0.9619	0.9618	0.01	−21.9403	−21.7564	0.95
10	1.0153	1.0150	0.02	−24.3252	−24.2654	0.16
11	0.9876	0.9873	0.03	−15.2850	−15.6475	2.30
12	0.9796	0.9794	0.02	−14.2821	−14.6575	2.51
13	1.0000	1.0000	0.00	−11.7628	−11.7565	0.54
14	1.0000	1.0000	0.00	−11.0728	−11.6585	5.00
15	1.0000	1.0000	0.00	−1.9977	−1.8974	5.00
16	1.0000	1.0000	0.00	−2.5971	−2.4634	5.00
17	0.9991	0.9991	0.00	2.1004	2.1075	0.33
18	1.0000	1.0000	0.00	3.5605	3.5676	0.19
19	0.9914	0.9910	0.04	−3.1704	−3.3857	0.48
20	0.9945	0.9947	0.02	−1.6226	−1.4574	2.30
21	1.0000	1.0000	0.00	4.3765	4.6747	2.10
22	1.0000	1.0000	0.00	10.6497	10.6575	0.07
23	1.0000	1.0000	0.00	0.0000	0.0000	0.00
24	0.9629	0.9627	0.02	−8.6198	−8.6657	0.52
39	1.0000	1.0000	0.00	−13.4055	−13.4765	0.52
40	1.0000	1.0000	0.00	−13.4055	−13.7658	2.60

Table 5.22: Comparison of the line flows for Case-9.

Line no.	*S. Bus*	*R. Bus*	*Original system (Active)*	*Equivalent system (Active)*	*% Error*	*Original system (Reactive)*	*Equivalent system (Reactive)*	*% Error*
61	**39**	**40**	0.9744	1.0543	--	−0.1336	0.2431	--
1	1	2	0.1362	0.1367	0.36	−0.2559	−0.2540	0.74
2	1	3	−0.1565	−0.1554	0.70	0.2662	0.2658	0.22
3	1	5	0.4605	0.4624	0.41	−0.0484	−0.0474	1.02
4	2	4	0.2996	0.2989	0.23	0.2284	0.2279	0.21
5	2	6	0.3867	0.3859	0.20	−0.3284	−0.3257	0.82
6	3	9	0.2022	0.2033	0.54	−0.1775	−0.1759	0.89
7	3	24	−2.1646	−2.1654	0.03	0.1045	0.1058	1.04
8	4	9	−0.4453	−0.4449	0.08	0.0923	0.0928	0.53
9	5	10	−0.2541	−0.2549	0.31	−0.1846	−0.1840	0.32
10	6	10	−0.9853	−0.9858	0.05	−0.6004	−0.6018	0.23
11	7	8	0.2502	0.2518	0.63	0.5094	0.5091	0.05
12	8	9	−0.7837	−0.7829	0.01	0.2611	0.2621	0.41
13	8	10	−0.6813	−0.6830	0.24	−0.1059	−0.1049	0.94
14	9	11	−1.3179	−1.3169	0.01	−0.1821	−0.1837	0.54
15	10	12	−2.0497	−2.0487	0.04	0.6703	0.6714	0.16
16	10	11	−1.8640	−1.8638	0.06	0.5345	0.5338	0.13
17	9	12	−1.4990	−1.4999	0.06	−0.0608	−0.0616	1.01
18	11	13	−1.4583	−1.4588	0.03	−0.0673	−0.0668	0.74
19	11	14	−1.7367	−1.7350	0.11	−0.0468	−0.0465	0.50
20	12	13	−1.1162	−1.1154	0.07	−0.2966	−0.2966	0.00
21	12	23	−2.4486	−2.4476	0.04	0.3235	0.3233	0.05
22	13	23	−2.1941	−2.1939	0.00	0.4135	0.4131	0.14
23	14	16	−3.6933	−3.6920	0.03	0.7148	0.7167	0.50
24	15	16	0.5958	0.5949	0.10	−0.0908	−0.0905	0.21
25D	15	21	−2.2138	−2.2129	0.00	0.3594	0.3599	0.32
26	15	24	2.2118	2.2119	0.00	0.4991	0.4993	0.20
27	16	17	−3.0896	−3.0898	0.00	0.5296	0.5256	0.31
28	16	19	0.4702	0.4708	0.01	0.2888	0.2886	0.05
29	17	18	−1.7460	−1.7464	0.13	0.1655	0.1656	0.01
30	17	22	−1.3760	−1.3768	0.02	0.1633	0.1646	0.42
31D	18	21	−0.5408	−0.5454	0.14	0.0456	0.0476	0.45
32D	19	20	−0.6704	−0.6726	0.02	−0.0223	−0.0228	1.32
33D	20	23	-1.3127	−1.3110	0.12	−0.0883	−0.0876	0.23
34	21	22	−1.5750	−1.5748	0.14	0.2193	0.2183	0.45
77D	1	40	2.8745	2.8742	0.13	0.0817	0.0819	0.20
78	13	39	0.9482	0.9488	0.04	−0.1311	−0.1319	0.60

5.4.1 Case-10: Outage of Line 22

In this case, the transmission line number 22 is considered to be physically out. Fast Decoupled Load Flow solution technique was applied for the solution of the network. The load flow results obtained, tables 5.23 and 5.24 show the results of the load flow analysis . The accuracy of the equivalent can be judged by the % age error between the results of a full system and its equivalent model. Comparison of load flow analysis for the two systems gives confidence to the equivalencing algorithm as %age errors between both systems are with in the specified limits.

Table 5.23: Comparison of bus voltages and angles of two systems for Case-10.

Bus No.	BusVoltage Orig.System p.u.	BusVoltage Eq.System p.u.	% Error	BusAngle Orig.System deg.	BusAngle Eq.System deg.	% Error
1	1.0000	1.0000	0.00	−26.8293	−26.4373	1.40
2	1.0000	1.0000	0.00	−26.9576	−26.7658	0.71
3	0.9452	0.9452	0.00	−23.2643	−23.5637	1.20
4	0.9583	0.9583	0.00	−28.7751	−28.5436	0.73
5	0.9931	0.9935	0.04	−29.2124	−29.5432	1.19
6	1.0413	1.0418	0.04	−32.0027	−32.3746	0.16
7	1.0000	1.0000	0.00	−34.2058	−34.8746	2.10
8	0.9634	0.9639	0.05	−34.6162	−34.8647	0.75
9	0.9598	0.9596	0.002	−25.7484	−25.8753	0.49
10	1.0137	1.0137	0.00	−28.2534	−28.3542	0.35
11	0.9872	0.9870	0.02	−19.3942	−19.4365	0.21
12	0.9756	0.9755	0.01	−18.1371	−18.9746	0.85
13	1.0000	1.0000	0.00	−16.9326	−16.5837	2.10
14	1.0000	1.0000	0.00	−14.0634	−14.8634	0.21
15	1.0000	1.0000	0.00	−4.0224	−4.7536	0.65
16	1.0000	1.0000	0.00	−4.5169	−4.8746	0.12
17	0.9992	0.9991	0.01	0.1439	0.1433	0.42
18	1.0000	1.0000	0.00	1.5864	1.5875	0.06
19	0.9910	0.9915	0.05	−4.2668	−4.2675	0.01
20	0.9940	0.9948	0.02	−2.0073	−2.0184	0.54
21	1.0000	1.0000	0.00	2.3864	2.3546	1.33
22	1.0000	1.0000	0.00	8.6728	8.6684	0.05
23	1.0000	1.0000	0.00	0.0000	0.0000	0.00
24	0.9601	0.9604	0.03	−11.0429	−11.7748	1.10
39	1.0000	1.0000	0.00	−16.8150	−16.6845	0.78
40	1.0000	1.0000	0.00	−17.0145	−17.7836	4.30

Table 5.24: Comparison of line flows of two systems for Case-10

Line no.	*S. Bus*	*R. Bus*	*Original system (Active)*	*Equivalent system (Active)*	*% Error*	*Original system (Reactive)*	*Equivalent system (Reactive)*	*% Error*
61	**39**	**40**	0.1981	0.1970	0.55	−0.0430	−0.0420	2.30
1	1	2	0.1557	0.1537	1.28	−0.2595	−0.2587	0.30
2	1	3	−0.1960	−0.1940	1.03	0.2900	0.2909	0.30
3	1	5	0.4805	0.4825	0.41	−0.0438	−0.0435	0.68
4	2	4	0.3057	0.3057	0.00	0.2366	0.2369	0.12
5	2	6	0.4001	0.4002	0.00	−0.3235	−0.3227	0.24
6	3	9	0.2836	0.2831	0.21	−0.1959	−0.1946	0.66
7	3	24	−2.2869	−2.2879	0.04	0.1406	0.1413	0.49
8	4	9	−0.4394	−0.4387	0.15	0.0995	0.0989	0.60
9	5	10	−0.2345	−0.2344	0.06	−0.1806	−0.1808	0.11
10	6	10	−0.9722	−0.9728	0.05	−0.5970	−0.5974	0.06
11	7	8	0.2502	0.2564	2.41	0.5238	0.5236	0.03
12	8	9	−0.7882	−0.7743	1.79	0.2712	0.2734	0.87
13	8	10	−0.6769	−0.6653	0.17	−0.1026	−0.1014	0.56
14	9	11	−1.2561	−1.2432	1.02	−0.2101	−0.2124	1.08
15	10	12	−2.0521	−2.0451	0.34	0.6989	0.6976	0.18
16	10	11	−1.8236	−1.8316	0.43	0.5119	0.5121	0.03
17	9	12	−1.4800	−1.4806	0.04	−0.0427	−0.0427	0.00
18	11	13	−0.9077	−0.9067	0.11	−0.1784	−0.1789	0.27
19	11	14	−2.1844	−2.1839	0.00	0.0396	0.0393	0.75
20	12	13	−0.4864	−0.4856	0.18	−0.4799	−0.4794	0.10
21	12	23	−3.0619	−3.0654	0.11	0.5527	0.5523	0.07
22	13	23	*out*	*out*	−−	*out*	*out*	−−
23	14	16	−4.1508	−4.1522	0.03	0.8489	0.8480	0.10
24	15	16	0.4913	0.4914	0.02	−0.0785	−0.0784	0.12
25D	15	21	−2.2257	−2.2354	0.04	0.3623	0.3628	0.13
26	15	24	2.3401	2.3421	0.43	0.5508	0.5500	0.03
27	16	17	−3.0658	−3.0643	0.04	0.5236	0.5234	0.05
28	16	19	−0.1342	−0.1336	0.06	0.3844	0.3846	0.24
29	17	18	−1.7250	−1.7248	0.01	0.1641	0.1645	0.24
30	17	22	−1.3728	−1.3726	0.01	0.1626	0.1626	0.00
31D	18	21	−0.5302	−0.5326	0.45	0.0441	0.0441	0.00
32D	19	20	−0.9724	−0.9729	0.05	0.0271	0.0271	0.10
33D	20	23	−1.6173	−1.6134	0.24	−0.0592	−0.0595	0.50
34	21	22	−1.5783	−1.5734	0.31	0.2201	0.2207	0.27
77D	1	40	3.3912	3.3945	0.09	0.1873	0.1872	0.10
78	13	39	−0.0519	−0.0514	0.96	−0.0205	−0.0203	0.98

5.5 Study System-D: Replication of RTS system

The aim of this section is the same as that of the previous section. However, the IEEE RTS is comparatively small. For this reason and in order to show the applicability of the proposed equivalent technique to larger system sizes, the dimension of the original RTS is duplicated (Appendix A). The duplication is done as follows: each individual RTS of the multiple RTS is identical, each individual RTS is linked by three lines. The single line diagram is shown in Figure 5.8 . The area of interest is defined as a full size RTS. Table 5.25 shows the comparison of the bus voltages and the bus angles in the area of interest. While Table 5.26 shows the comparison of original system with its equivalent in terms of line flows. Figure 5.9 shows the equivalent system for case-11. The dimension of this study system is same as that of system-C but different configuration is selected to validate the equivalencing algorithm. RTS system is connected to the north part of IEEE-24 bus system which is a power deficient area. Shaded area shows the external system for the study case. Percentage error between the results of load flow for the original system and the equivalent system is quite small which validates the equivalencing algorithm.

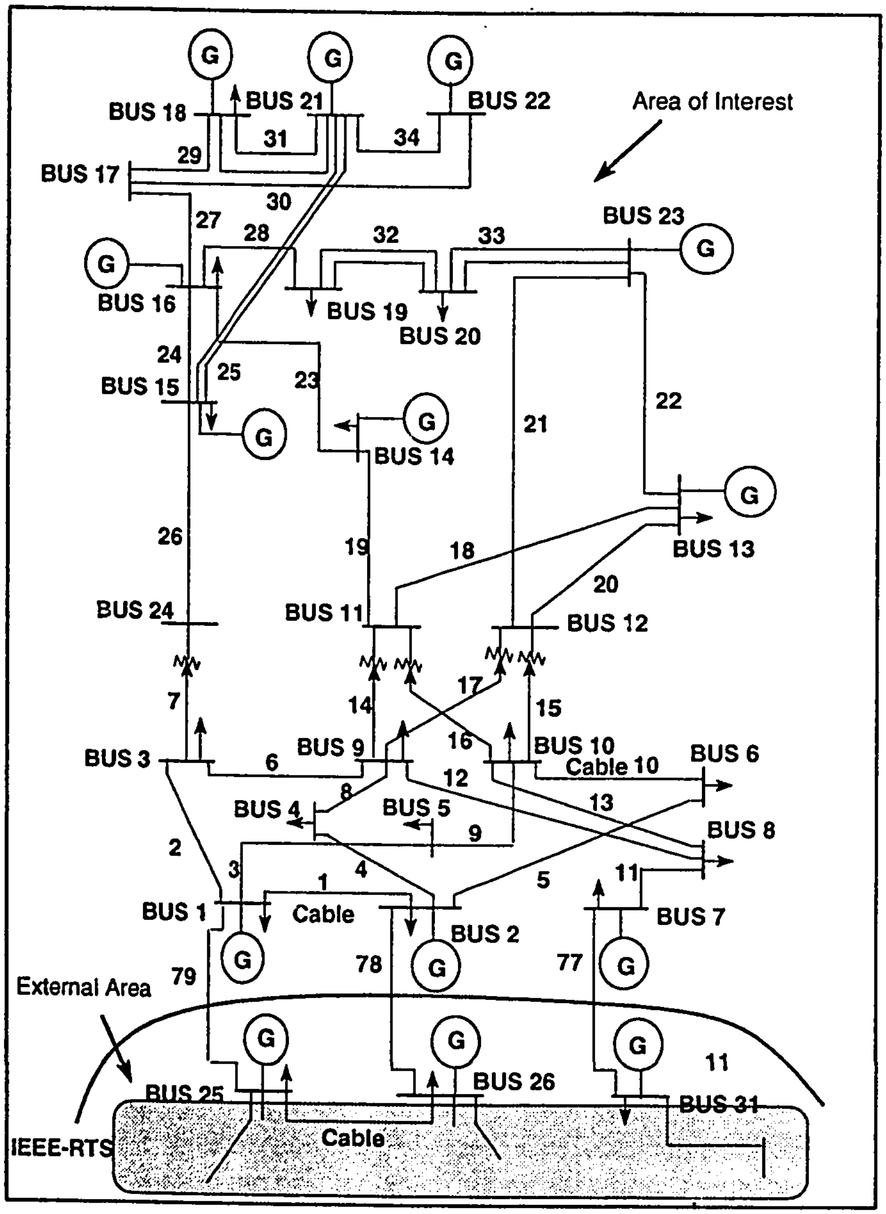

Figure 5.8: The single line diagram for two interconnected RTS systems Case-11

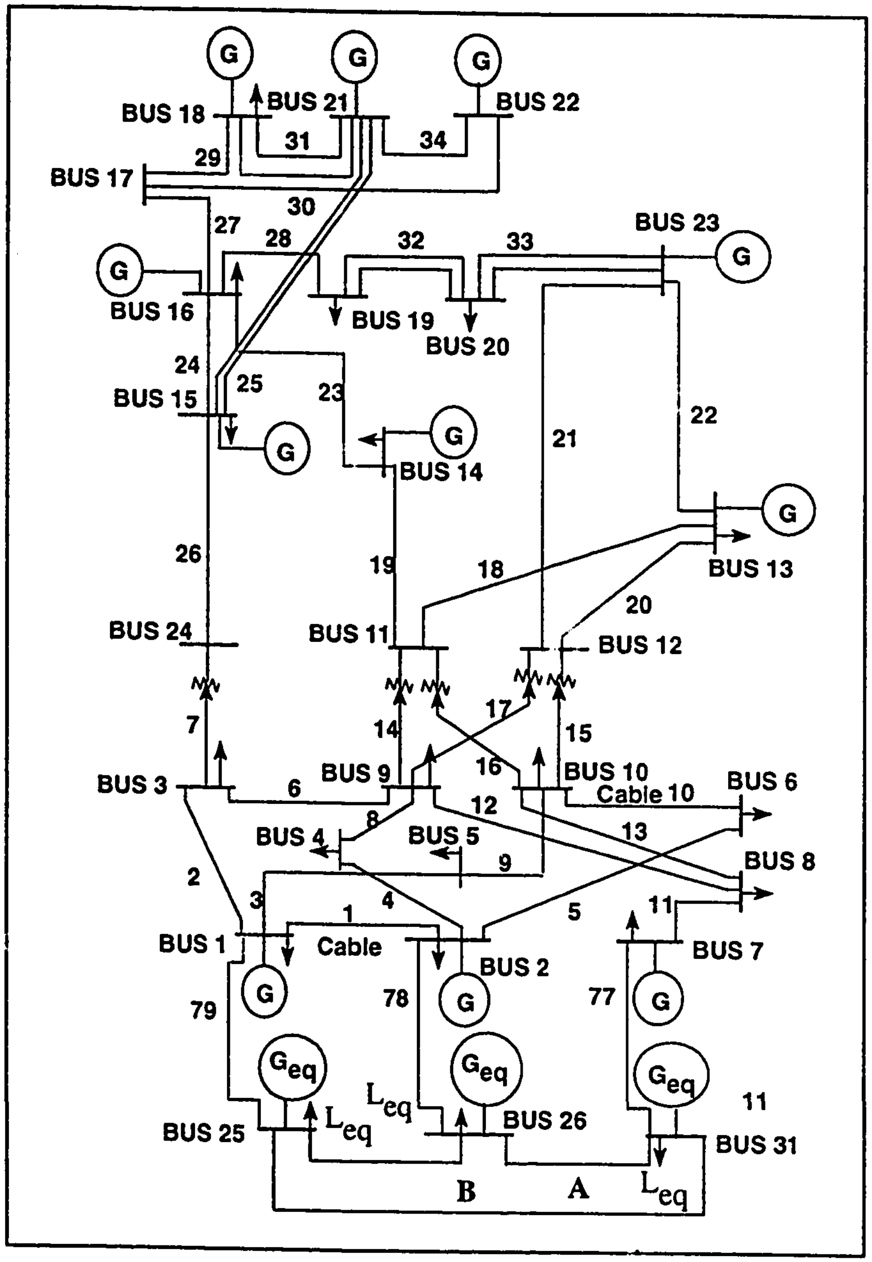

Figure 5.9: The single line diagram for two interconnected RTS systems Case-11(Equivalent System)

Table 5.25: Comparison of the bus voltages and the bus angles for Case-11.

Bus No.	*BusVoltage Orig.System p.u.*	*BusVoltage Eq.System p.u.*	*% Error*	*BusAngle Orig.System deg.*	*BusAngle Eq.System deg.*	*% Error*
1	1.0000	1.0000	0.00	−72.0063	−72.9865	1.34
2	1.0000	1.0000	0.00	−72.2779	−71.7563	0.72
3	0.8538	0.8532	0.07	−46.8539	−46.5648	0.61
4	0.8826	0.8822	0.04	−62.8479	−61.7846	1.70
5	0.9309	0.9304	0.05	−65.6187	−64.9038	1.09
6	0.9482	0.9482	0.00	−63.4571	−63.4537	0.00
7	1.0000	1.0000	0.00	−85.0719	−85.5632	0.57
8	0.8798	0.8794	0.04	−75.8576	−75.1452	0.94
9	0.8625	0.8622	0.03	−48.2684	−48.75634	1.01
10	0.9121	0.9127	0.06	−54.1950	−54.7532	1.02
11	0.9278	0.9271	0.075	−32.4019	−32.9847	1.76
12	0.8851	0.8849	0.02	−29.9143	−29.8765	0.13
13	1.0000	1.0000	0.00	−23.2443	−23.3224	0.33
14	1.0000	1.0000	0.00	−24.4297	−24.8764	1.79
15	1.0000	1.0000	0.00	−12.9375	−12.3524	4.5
16	1.0000	1.0000	0.00	−12.3655	−12.8734	3.9
17	0.9994	0.9999	0.05	−8.0775	−8.4735	4.67
18	1.0000	1.0000	0.00	−6.8136	−6.4637	5.13
19	0.9863	0.9866	0.03	−8.7611	−8.7483	0.15
20	0.9903	0.9905	0.02	−3.5765	−3.7696	5.12
21	1.0000	1.0000	0.00	−6.1762	−6.3475	2.69
22	1.0000	1.0000	0.00	0.2437	0.2465	1.13
23	1.0000	1.0000	0.00	0.0000	0.0000	0.00
24	0.8958	0.8956	0.02	−24.2898	−24.0965	0.80
25	1.0000	1.0000	0.00	−83.9800	−83.9575	0.02
26	1.0000	1.0000	0.00	−83.9292	−83.9764	0.05
31	1.0000	1.0000	0.00	−95.3090	−94.9864	0.34

Table 5.26: Comparison of line flows of two systems for Case-11

Line no.	*S. Bus*	*R. Bus*	*Original system (Active)*	*Equivalent system (Active)*	*% Error*	*Original system (Reactive)*	*Equivalent system (Reactive)*	*% Error*
1	1	2	0.3297	0.3245	1.57	−0.2914	−0.2976	2.20
2	1	3	−1.3505	−1.3519	0.10	1.3963	1.3977	0.05
3	1	5	−0.9353	−0.9351	2.13	1.1159	1.1354	2.05
4	2	4	−0.8223	−0.8229	0.07	1.2667	1.278	0.30
5	2	6	−0.6304	−0.6367	0.09	0.4654	0.4624	0.64
6	3	9	0.1286	0.1267	1.55	−0.1073	−0.1075	0.18
7	3	24	−3.4892	−3.4876	0.04	0.3673	0.3687	0.37
8	4	9	−1.6342	−1.6574	1.39	0.8186	0.8145	0.50
9	5	10	−1.6918	−1.6587	1.90	0.8160	0.8197	0.45
10	6	10	−2.0219	−2.0576	1.73	0.1121	0.1134	1.10
11	7	8	−1.6311	−1.6764	0.09	2.5569	2.5576	0.02
12	8	9	−1.8468	−1.8654	0.07	1.0755	1.0767	0.11
13	8	10	−1.6406	−1.5764	2.50	0.5787	0.5798	0.18
14	9	11	−2.6151	−2.6473	0.02	−0.2354	−0.2356	0.08
15	10	12	−3.9236	−3.9231	0.01	1.2524	1.2545	0.16
16	10	11	−3.7278	−3.7237	0.10	0.6528	0.6534	0.10
17	9	12	−2.8578	−2.8549	0.10	0.3095	0.3076	0.61
18	11	13	−3.1993	−3.1948	0.17	−0.7924	−0.7998	0.91
19	11	14	−3.2054	−3.2093	0.01	−1.0124	−1.0145	0.20
20	12	13	−2.3792	−2.3745	0.01	−1.7449	−1.7467	0.10
21	12	23	−4.4756	−4.4767	0.02	0.6638	0.6656	0.27
22	13	23	−4.3717	−4.3749	0.07	1.4092	1.4087	0.07
23	14	16	−5.2159	−5.2123	0.06	1.1977	1.1765	1.70
24	15	16	−0.5677	−0.5686	0.19	0.0569	0.0576	1.21
25D	15	21	−2.3466	−2.3456	0.04	0.3923	0.3987	1.61
26	15	24	3.6409	3.6426	0.05	1.8219	1.8276	0.31
27	16	17	−2.8238	−2.8267	0.03	0.4635	0.4676	0.87
28	16	19	−2.5542	−2.5534	0.03	0.9852	0.9873	0.21
29	17	18	−1.5109	−1.5165	0.39	0.1495	0.1445	3.30
30	17	22	−1.3400	−1.3434	0.25	0.1557	0.1540	1.09
31D	18	21	−0.4225	−0.4256	0.01	0.0290	0.0276	4.20
32D	19	20	−2.1934	−2.1674	1.10	0.2424	0.2489	1.80
33D	20	23	−2.8591	−2.8556	0.24	−0.0054	−0.0053	1.76
34	21	22	−1.6114	−1.6145	0.18	0.2281	0.2281	0.00
35	25	26	−1.8914	−1.6895	−−	0.2981	0.3001	−−
77	1	25	2.3967	2.3945	0.02	0.0057	0.0051	3.5
78	2	26	2.3326	2.3365	0.17	−0.0029	−0.0022	3.4
79	7	31	1.8815	1.8854	0.21	−0.1985	−0.1984	0.05

Chapter 6

Adequacy Evaluation of The Proposed Equivalent

6.1 Introduction

The focal point of this chapter is to show the comparison between the systems and their equivalent models, and to confirm the compatibility of the adequacy indices results for both systems. These analysis consist of line outages, generating unit outages and a combination of line(s) and unit(s) variations. The sensitivity analysis are conducted inside a defined area of interest for the original system as well as the equivalent system.

6.2 Case Studies

For the analysis of IEEE RTS system, IEEE RTS is assumed to have a constant load through out one year of operation. This type of simplification is found very often in reliability literature, because it can detect the main system weakness with a reduced computing time and produces the annualised indices.

The cases in this chapter demonstrate the adequacy indices for the original IEEE RTS system which has been equivalenced to an area of interest and boundary buses coupled to the proposed equivalent models at which equivalent boundary lines generator model and the load models are depicted. The cases which are discussed in the previous chapter and were proved to be efficient in terms of the load flow will be tried to evaluate the adequacy of the system. An AC load flow solution is used to evaluate the adequacy of the system. The adequacy indices are calculated subject up to second order line outages. Moreover, sensitivity analysis are conducted inside each area of interest. These sensitivity analysis are based on the outage of the specific generating units in the area of interest of the original system and its equivalent.

Many case studies were conducted but only a representative set are included in this thesis.

6.3 Study System-A

6.3.1 Case-1: Reference case

The total load, total generation and the number of lines of the two systems, the original system and the equivalent system are shown in Table 6.1 This study case is termed as case-1. System 1 is the original system and system 2 represents the equivalent system.

Table 6.1: System Configuration For Case-1

System	No. of buses	No. of Lines	Total gen. (MW)	Total Load (MW)
Original	24	34	3505	2850.0
Equivalent	20	28	3505	2850.0

The adequacy analysis for this case shows the adequacy behavior of the equivalent system compared with its original system under the impact of up to second order line outages. Table 6.2 shows the comparison of the expected load curtailed for the original system and the equivalent system.

The maximum load cut due to a single line outage was observed to be 44.66 MW with the frequency of 0.00030385 when sensitivity analysis was conducted on the original system and it happened when line LI10 was out. Using the equivalent model the maximum load cut was 44.68 MW and was observed in state when line LI10 was out. The buses which could not maintain constant voltages were 1, 2 and

Table 6.2: Expected load curtailed for case-1

Expected Load Curtailed					
Cause	System	Amount (MW)	Energy	Duration	Frequency
Busbar Isolation	1	0.221	1.43	0.011	0.002
	2	0.221	1.44	0.011	0.002
Voltage Violation	1	7.31	122.15	2.73	0.163
	2	7.24	120.4	2.67	0.169
MVAR Violation	1	0.041	0.37	0.01	0.001
	2	0.036	0.009	0.01	0.001

3 in both the original system and the equivalent when states up to second order were considered.

Table 6.3: Load point indices for outage case-1

Busbar No.	System	Line Over Load	
		Prob.	Energy
4	1	0.148E-06	0.115E00
	2	0.179E-06	0.116E00
5	1	0.143E-06	0.884E-01
	2	0.173E-06	0.888E-01
6	1	0.704E-06	0.837E+00
	2	0.704E-06	0.840E+00

The above tables show a good comparison of the equivalent system with the original system for the reference case. This prove the validity of the equivalent model for the AC adequacy analysis of a power system. The following figure 6.1 shows the comparison of the two studies in term of computer time. Table 6.4 gives the information about system indices. It can be shown that both, the original system

Table 6.4: Busbar reliability Indices case-1

Busbar Reliability Indices							
Busbar No.	System	Voltage Violation			MVAR violation		
		Prob.	Freq.	Energy	Prob	Freq.	Energy
3	1	0.620E-6	0.866E-3	0.326	0.400E-6	0.422E-3	0.826E-2
	2	0.406E-6	0.646E-3	0.279	0.390E-6	0.422E-3	0.820E-2
4	1	0.180E-6	0.206E-3	0.638E-2	0.175E-5	0.104E-2	0.116E-1
	2	0.143E-6	0.169E-3	0.625E-2	0.098E-5	0.100E-2	0.115E-1
6	1	0.311E-3	0.162	0.121E+3			
	2	0.247E-3	0.137	0.962E+2			
8	1	0.201E-6	0.265E-3	0.513E-1	0.175E-5	0.104E-2	0.124E-1
	2	0.241E-6	0.215E-3	0.510E-1	0.174E-5	0.102E-2	0.122E-1
9	1				0.242E-5	0.181E-2	0.715E-1
	2				0.240E-5	0.182E-2	0.714E-1

and the equivalent system have of low voltage at buses 3,4,6 and 8 while MVAR violation occurred at buses 3,4,8 and 9 for both the systems. Adequacy indices for both systems are in close agreement as can be seen from the results. Figure 6.2 gives the information of the number of states in both cases. The execution time is reduced due to the reduction in the number of states.

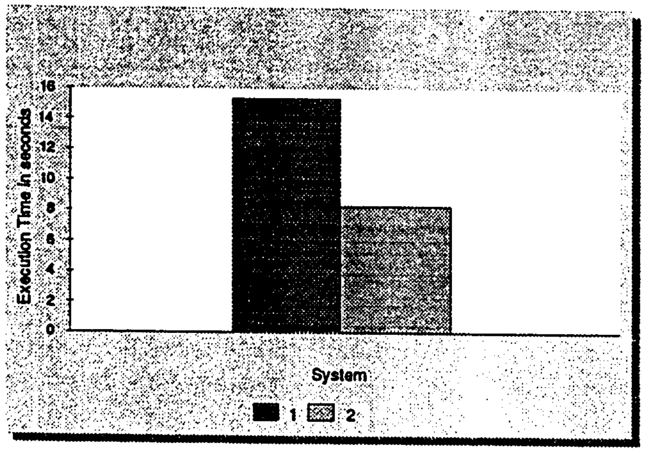

Figure 6.1: Comparison of execution time for both systems: Case-1.

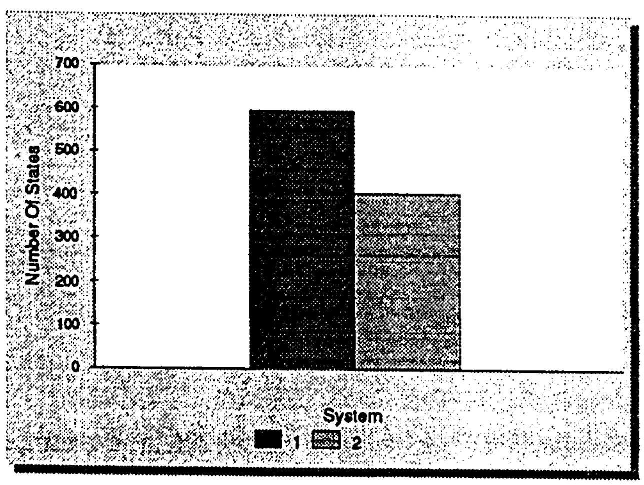

Figure 6.2: Comparison of the states for both systems(Case-1).

6.3.2 Case-2: Outage of Line 19

In the previous section the adequacy analysis is conducted for the reference case when all the facilities are present in the system. In this case a contingency is applied within the area of interest and then adequacy is evaluated for both systems so that the model is proved to be applicable for the conditions other than base case. Tables 6.5, 6.6 and 6.7 show adequacy indices of the system. System 1 is the original system and system 2 represents the equivalent system. System indices are shown in table 6.5.

Table 6.5: Case-2: Expected load curtailed

Expected Load Curtailed					
Cause	System	Amount (MW)	Energy (MWh)	Duration	Frequency
Busbar Isolation	1	75.87	810.92	4.186	0.396
	2	75.30	810.99	4.186	0.389
Insufficient Generation	1	0.005	0.04	0.003	0.00
	2	0.006	0.05	0.003	0.00
Voltage Violation	1	7.508	124.07	2.78	0.168
	2	6.472	112.21	2.206	0.143
MVAR Violation	1	0.091	0.83	0.015	0.168
	2	0.094	0.81	0.018	0.002
Line Overload	1	0.001	0.02	0.006	0.00
	2	0.002	0.04	0.005	0.00

The maximum load curtailed for bus isolation relief measure is 193.9 MW when LI23 is out with the frequency of 4.678E-4 for original system, in case of equivalent it is 193.9MW with the probability of 4.57E-4 when LI23 was out. The max. load curtailed needed for the corrective action of the voltage violation problem is 125.95 MW with the probability of 1.6E-7 when original system is analysed, in case of the equivalent system it is 124.9 MW with the probability of 9.0E-8, this load is being curtailed outage of lines, LI28 and LI07. The second order outages are considered

Table 6.6: Case-2: load point indices for outage

Busbar No.	System	Insuff. Gen.		Busbar Isol.		Line Over.	
		Prob.	Energy.	Prob.	Energy	Prob	Freq.
1	1	0.284E-6	0.253E-2				
	2	0.285E-6	0.258E-2				
3	1	0.368E-6	0.631E-2				
	2	0.369E-6	0.625E-2				
4	1			0.178E-6	0.115		
	2			0.170E-6	0.115		
5	1			0.143E-6	0.885E-1	0.709E-6	0.167E-1
	2			0.143E-6	0.888E-1	0.654E-6	0.284E-1
6	1			0.707E-6	0.841		
	2			0.705E-6	0.837		
9	1	0.284E-6	0.410E-2				
	2	0.285E-6	0.417E-2				

for the evaluation of the adequacy analysis. The line no. 9 is considered to be out for original system and equivalent system. The reliability indices are calculated for both systems for the area of interest. These are reproduced in the following tables which gives a good comparison for both systems.

Table 6.7 shows that problem of voltage violation occurred at buses 3,4,6,8,9 and 10 for both the systems and indices obtained are quite close to each other. Simmilarly the problem of MVAR violation occurred at buses 3,4,5,6,8,9,10 and 13

Table 6.7: Case-2: Busbar Reliability Indices

Busbar Reliability Indices							
Busbar No.	System	Voltage Violation			MVAR violation		
		Prob.	Freq.	Energy	Prob	Freq.	Energy
3	1	0.625E-5	0.534E-2	0.190E+1	0.625E-6	0.848E-3	0.167E-1
	2	0.503E-5	0.452E-2	0.154E+1	0.618E-6	0.820E-3	0.160E-1
4	1	0.230E-5	0.325E-3	0.109E-1	0.507E-5	0.332E-2	o.456E-1
	2	0.232E-6	0.305E-3	0.135E-1	0.418E-5	0.330E-2	0.459E-1
5	1				0.418E-5	0.330E-2	0.105E-1
	2				0.507E-5	0.474E-2	0.114E-1
6	1	0.247E-3	0.137	0.963E+2	0.353E-6	0.417E-3	0.824E-1
	2	0.311E-3	0.162	0.121E+3	0.321E-6	0.410E-3	0.653E-1
8	1	0.589E-6	0.7904E-3	0.171	0.417E-5	0.330E-2	0.907E-1
	2	0.611E-6	0.826E-3	0.170	0.418E-5	0.330E-2	0.907E-1
9	1	0.203E-6	0.216E-3	0.700E-1	0.432E-5	0.357E-2	0.104
	2	0.269E-6	0.381E-3	0.716E-1	0.507E-5	0.474E-2	0.111
10	1				0.418E-5	0.330E-2	0.163
	2				0.507E-5	0.474E-2	0.188
13	1	0.341E-6	0.424E-3	0.203	0.418E-5	0.330E-2	0.226
	2	0.272E-6	0.410E-3	0.200	0.410E-5	0.320E-2	0.220

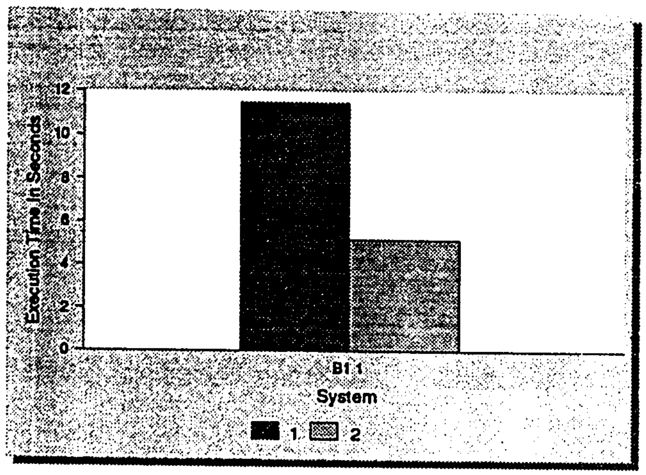

Figure 6.3: Comparison of execution time for both systems: case-2.

for both the systems as shown by table 6.7. Figure 6.3 gives the information about the execution time of both systems when line 19 is forced to be out.

6.3.3 Case-3: Outage of Line no. 18

The line no. 18 is taken out physically from the system and the adequacy analysis is carried out, utilizing the equivalent model. The adequacy indices are found to be in close agreement. The results of the analysis are tabulated below to observe the validity of the equivalent. The indices are calculated considering the outages up to second order. Tables 6.8, 6.9 and 6.10 show adequacy indices of the two systems. System 1 is original system and system 2 represents the equivalent system.

Table 6.8: Expected load curtailed: case-3

Expected Load Curtailed					
Cause	System	Amount (MW)	Energy	Duration	Frequency
Busbar Isolation	1	0.221	1.43	0.011	0.002
	2	0.221	1.44	0.011	0.002
Voltage Violation	1	7.588	124.76	2.781	0.168
	2	6.908	120.87	2.686	0.143
MVAR Violation	1	0.201	2.12	0.026	0.003
	2	1.20	3.43	0.063	0.135
Line Overload	1	0.001	0.02	0.006	0.0
	2	0.001	0.02	0.005	0.00

The maximum load curtailed for contingency when line no. 16 and 15 is observed to be 3.93 with the probability of 7.0E-7 and the energy curtailed was 0.02 MWH for the original system. The maximum load curtailed for the equivalent system is 3.92 with the frequency of 5.6E-7 when the same lines are out from the system. The maximum load curtailed per state is 863.34 MW with the probability of 4.0E-8 for original system, and for equivalent maximum load curtailed observed is 863.34 MW with the probability of 4.1E-8. As can be seen from the table 6.9, the original system and its equivalent system can have problem of bus isolation on buses 4,5,6 and 8 while the problem of line overload can occur on bus 8 of both the systems. The

Table 6.9: load point indices for outage: case-3

Busbar No.	System	Busbar Isol.		Line Over.	
		Prob.	Energy	Prob	Freq.
4	1	0.178E-6	0.115		
	2	0.179E-6	0.116		
5	1	0.143E-6	0.885E-1		
	2	0.143E-6	0.888E-1		
6	1	0.705E-6	0.837		
	2	0.707E-6	0.841		
8	1			0.709E-6	0.243E-1
	2			0.674E-6	0.240E-1

following table 6.10 gives the information about bus indices for the two systems. It can be seen that problem of voltage violation occurred at buses 3,4,6,8 and 9 for the two systems and MVAR violation occurred at buses 1,2,3,4,6,8,9 and 10 for the two systems.

Comparison for the time of execution for the two cases could be obtained from the following figure 6.4.

Table 6.10: Busbar reliability Indices: case-3

Busbar Reliability Indices							
Busbar No.	System	Voltage Violation			MVAR violation		
		Prob.	Freq.	Energy	Prob	Freq.	Energy
1	1				0.146E-5	0.149E-2	0.588E-2
	2				0.152E-5	0.149E-2	0.671E-2
3	1	0.469E-5	0.414E-2	0.152E+1	0.115E-5	0.108E-2	0.406E-1
	2	0.365E-5	0.333E-2	0.122E+1	0.110E-5	0.104E-2	0.375E-1
4	1	0.279E-6	0.397E-3	0.159E-1	0.719E-5	0.523E-2	0.137
	2	0.222E-6	0.325E-3	0.103E-1	0.645E-5	0.497E-2	0.141
5	1				0.719E-5	0.523E-2	0.521E-1
	2				0.709E-5	0.519E-2	0.510E-1
6	1	0.311E-3	0.162	0.121E+3			
	2	0.300E-3	0.158	0.968E+2			
8	1	0.736E-6	0.104E-2	0.199	0.719E-5	0.523E-2	0.255
	2	0.699E-6	0.914E-3	0.181	0.654E-2	0.488E-2	0.245
9	1	0.577E-6	0.759E-3	0.380	0.755E-5	0.565E-2	0.279
	2	0.541E-6	0.778E-3	0.380	0.699E-5	0.557E-2	0.274
10	1				0.755E-5	0.565E-2	0.460
	2				0.750E-2	0.560E-2	0.456

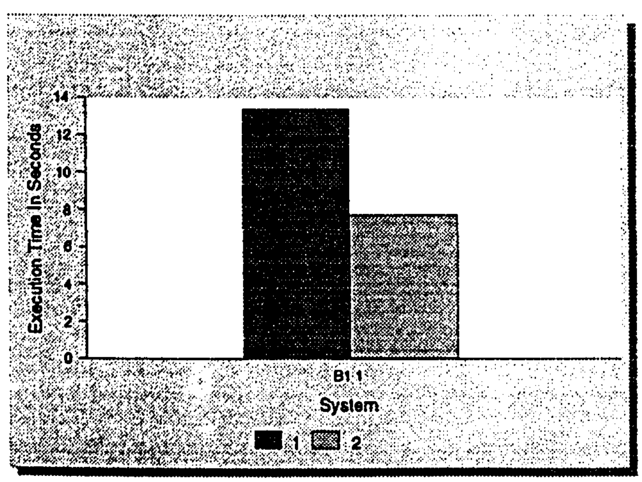

Figure 6.4: Comparison of the execution time for both systems : Case-3.

6.4 Reliability Analysis Conducted For Study System-B

6.4.1 Case-4: Reference Case

Adequacy analysis was carried out for the study system-B which is discussed in the previous chapter (chapter 5). This case is also called case-4. The load, generation, line and the busbar information for the original system and the equivalent system is given in Table 6.11. All transmission facilities are assumed to be available for this case (reference case).

Table 6.11: System configuration for case-4

System	No. of buses	No. of Lines	Total gen. (MW)	Total Load (MW)
Original	24	34	3405.10	2850.00
Equivalent	18	26	3405.10	2850.00

The load curtailed required for the corrective action are given in table 6.12. System 1 is the original system and system 2 is equivalent system. Expected load curtailed is a system index that could not provide much of the information about the reliability of the system. The curtailed load in the external area could be achieved by subtracting the curtailed load in the area of interest from the load curtailed for the full system.

Figures 6.5 shows a comparison of the execution time and figure 6.6 shows a

Table 6.12: Expected load curtailed: Case-4 (ref. case)

Expected Load Curtailed					
Cause	System	Amount (MW)	Energy	Duration	Frequency
Busbar Isolation	1	0.221	1.43	0.011	0.002
	2	0.221	1.42	0.011	0.002
Voltage Violation	1	7.310	122.15	2.733	0.163
	2	6.902	114.54	2.456	0.154
MVAR Violation	1	0.041	0.37	0.010	0.001
	2	0.008	0.05	0.001	0.167

Table 6.13: Busbar reliability Indices for Case-4(ref. case)

Busbar Reliability Indices							
Busbar No.	System	Voltage Violation			MVAR violation		
		Prob.	Freq.	Energy	Prob	Freq.	Energy
3	1	0.620E-6	0.866E-3	0.326	0.400E-6	0.422E-3	0.826E-2
	2	0.554E-6	0.739E-3	0.316	0.390E-6	0.367E-3	0.820E-2
4	1	0.180E-6	0.206E-3	0.638E-2	0.175E-5	0.104E-2	0.116E-1
	2	0.168E-6	0.198E-3	0.576E-2	0.170E-5	0.100E-2	0.115E-1
6	1	0.311E-3	0.162	0.121E+3			
	2	0.317E-3	0.175	0.124E+3			
8	1	0.201E-6	0.265E-3	0.513E-1	0.175E-5	0.104E-2	0.124E-1
	2	0.206E-6	0.279E-3	0.497E-1	0.170E-5	0.100E-2	0.100E-1
9	1				0.242E-5	0.181E-2	0.715E-1
	2				0.240E-5	0.179E-2	0.710E-1

Table 6.14: load point indices for outage Case-4(ref. case)

Busbar No.	System	Busbar Isolation	
		Prob.	Energy
	1	0.178E-6	0.115
4	2	0.179E-6	0.116
	1	0.143E-6	0.884E-1
5	2	0.143E-6	0.889E-1
	1	0.704E-6	0.837
6	2	0.708E-6	0.842E-1

comparison of the number of states of both systems.

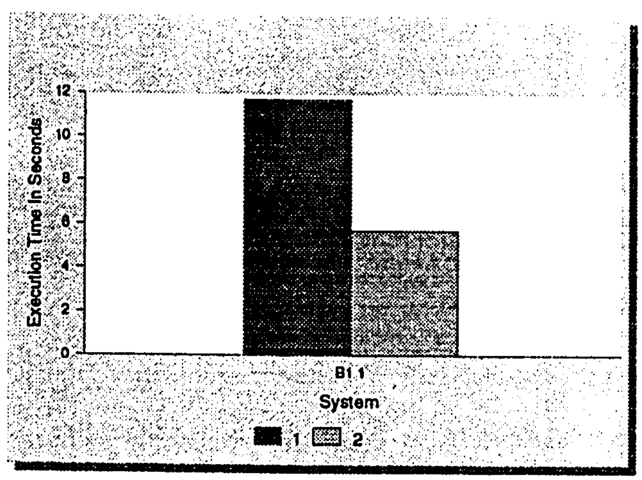

Figure 6.5: Comparison of execution time for both systems for case-4 .

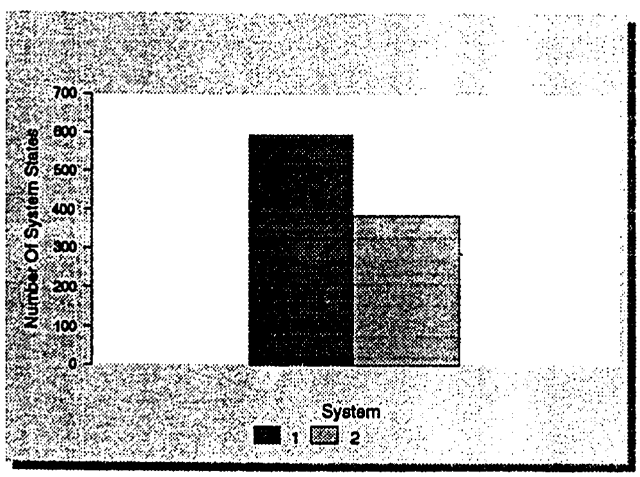

Figure 6.6: Comparison of the no. of states of both systems for case-4.

6.4.2 Case-5: Outage of Line 3

In the previous sub-section the adequacy analysis is carried out for the reference case when all the facilities are present in the system. In this case a contingency is applied with in the area of interest and then adequacy is evaluated for both systems so that the model is proved to be applicable for conditions other than base case.

Table 6.15 gives the information about the load and the configuration of the two systems.

Table 6.15: System configuration for case-5

System	No. of buses	No. of Lines	Total gen. (MW)	Total Load (MW)
Original	24	33	3505	2850
Equivalent	18	25	3505	2850

Up to second order outages are considered for the evaluation of the adequacy analysis. Line no. 3 is taken out of the original system and the equivalent system. The reliability indices are calculated for both systems, in the area of interest. These are reproduced in tables 6.16, 6.17 and 6.18 which give a good comparison of both systems.

The maximum load curtailed for a single cause is 44.58 MW for original system when line no.10 is out and for equivalent, maximum load curtailed is observed to be 44.59 MW, for same line LI10 outage, to alleviate the problem of voltage violation. The maximum energy and load curtailed per state is 0.57 MWH and 490 MW with

Table 6.16: Expected load curtailed: Case-5

Expected Load Curtailed					
Cause	System	Amount (MW)	Energy	Duration	Frequency
Busbar Isolation	1	24.926	242.58	3.407	0.350
	2	24.676	242.50	3.408	0.346
Voltage Violation	1	7.319	122.47	2.741	0.164
	2	7.270	120.47	2.17	0.139
MVAR Violation	1	0.057	0.54	0.01	0.001
	2	0.041	0.46	0.009	0.001
Line Overload	1	0.040	0.86	0.007	0.00
	2	0.036	0.82	0.007	

probability of 1.3E-7 for both cases (original and equivalent system)

Fig. 6.7 gives the information of both systems when line no. 3 is out. Table 6.18 gives information about system indices. System can have a problem of voltage violation at buses 3,4,5,6 and 8 while MVAR violation can occur at buses 4,5,8 and 10. Results shown give confidence to the equivalent model as indices obtained in case of the original system and the equivalent system are very close to each other.

Table 6.17: load point indices for outage: case-5

Busbar No.	System	Busbar Isol.		Line Over.	
		Prob.	Energy	Prob	Freq.
4	1	0.178E-6	0.115		
	2	0.179E-6	0.116		
5	1	0.388E-3	0.241E+3		
	2	0.388E-3	0.241E+3		
6	1	0.705E-6	0.837	0.709E-6	0.515
	2	0.709E-6	0.842	0.726E-6	0.524
8	1			0.751E-6	0.288
	2			0.726E-6	0.285
9	1			0.420E-7	0.541E-1
	2			0.400E-7	0.510E-1

Table 6.18: Busbar reliability Indices: case-5

Busbar Reliability Indices							
Busbar No.	System	Voltage Violation			MVAR violation		
		Prob.	Freq.	Energy	Prob	Freq.	Energy
3	1	0.818E-6	0.108E-2	0.391			
	2	0.747E-6	0.963E-3	0.348			
4	1	0.180E-6	0.206E-3	0.685E-2	0.236E-5	0.218E-2	0.205E-1
	2	0.143E-6	0.169E-3	0.598E-2	0.216E-5	0.210E-2	0.200E-1
5	1	0.124E-5	0.477E-3	0.492	0.236E-5	0.218E-2	0.377E-1
	2	0.127E-5	0.537E-3	0.498	0.230E-5	0.215E-2	0.376E-1
6	1	0.300E-3	0.160	0.121E+3			
	2	0.317E-3	0.164	0.123E+3			
8	1	0.201E-6	0.265E-3	0.542E-1	0.236E-5	0.218E-2	0.598E-1
	2	0.206E-6	0.272E-3	0.539E-1	0.230E-5	0.215E-2	0.591E-1
10	1				0.236E-5	0.218E-2	0.121
	2			0.230E-5	0.215E-2		0.120

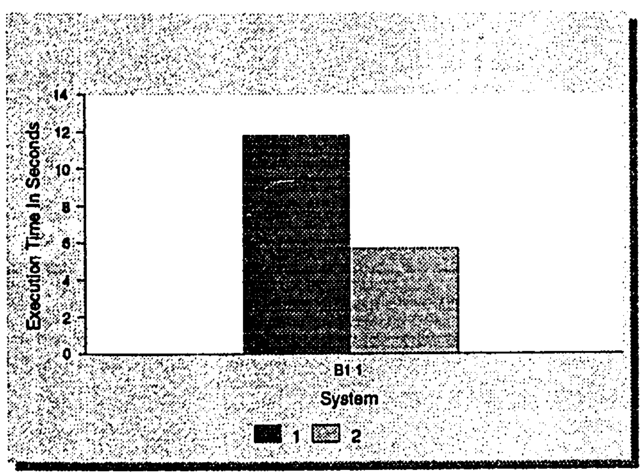

Figure 6.7: Comparison of execution time for both systems: Case-5.

6.4.3 Case-6: Outage of Line 19

In this section the line no. 19 is taken out (from the study system-B) and adequacy analysis is carried out for original system and equivalent system. The comparison of both results are shown in following tables ref23.0, 6.20 and 6.21. The equivalencing approach established in this thesis is proved to be satisfactory in the situations other than the base case.

Table 6.19: Expected load curtailed: case-6

Expected Load Curtailed					
Cause	System	Amount (MW)	Energy	Duration	Frequency
Busbar Isolation	1	75.87	810.92	4.186	0.396
	2	75.03	810.90	4.186	0.388
Insufficient Generation	1	0.005	0.04	0.003	0.00
	2	0.006	0.05	0.003	0.00
Voltage Violation	1	7.508	124.07	2.78	0.168
	2	6.452	112.91	2.66	0.153
MVAR Violation	1	0.091	0.83	0.015	0.168
	2	0.089	0.81	0.010	0.002
Line Overload	1	0.001	0.02	0.006	0.00
	2	0.002	0.06	0.006	0.00

The maximum load curtailed for bus isolation relief measure is 193.9 MW when LI23 is out with probability of 4.678E-4 for original system, and for the same corrective action, in case of equivalent it is 193.9MW the probability of 4.57E-4 when LI23 is out. The max. load curtailed for the corrective action of the voltage violation problem, is 125.95 MW with probability of 1.6E-7 when original system is analysed, in case of the equivalent system, it is 124.9 MW with probability of 9.0E-8, this load is curtailed the consideration of LI28 and LI07 out.

Table 6.20: load point indices for outage: case-6

Busbar No.	System	Insuff. Gen.		Busbar Isol.		Line Over.	
		Prob.	Energy.	Prob.	Energy	Prob	Freq.
1	1	0.284E-6	0.253E-2				
	2	0.280E-6	0.250E-2				
3	1	0.368E-6	0.631E-2				
	2	0.369E-6	0.625E-2				
4	1			0.178E-6	0.115		
	2			0.179E-6	0.116		
5	1			0.143E-6	0.885E-1	0.709E-6	0.167E-1
	2			0.143E-6	0.890E-1	0.726E-6	0.184E-1
6	1			0.707E-6	0.841		
	2			0.709E-6	0.842		
9	1	0.284E-6	0.410E-2				
	2	0.280E-6	0.411E-2				

The execution time can be compared by the following figure 6.8

Table 6.21: Busbar reliability Indices for case-6

Busbar Reliability Indices								
Busbar No.	System	Voltage Violation			MVAR violation			
		Prob.	Freq.	Energy	Prob	Freq.	Energy	
3	1	0.625E-5	0.534E-2	0.190E+1	0.625E-6	0.848E-3	0.167E-1
	2	0.647E-5	0.581E-2	0.197E+1	0.617E-6	0.840E-3	0.163E-1
4	1	0.230E-5	0.325E-3	0.109E-1	0.507E-5	0.332E-2	o.456E-1
	2	0.232E-5	0.315E-3	0.115E-1	0.498E-5	0.334E-2	0.450E-1
5	1				0.418E-5	0.330E-2	0.105E-1
	2				0.508E-5	0.374E-2	0.112E-1
6	1	0.247E-3	0.137	0.963E+2	0.353E-6	0.417E-3	0.824E-1
	2	0.310E-3	0.160	0.120E+3	0.341E-6	0.414E-3	0.753E-1
8	1	0.589E-6	0.790E-3	0.171	0.417E-5	0.330E-2	0.907E-1
	2	0.610E-6	0.726E-3	0.168	0.428E-5	0.333E-2	0.905E-1
9	1	0.203E-6	0.216E-3	0.700E-1	0.432E-5	0.357E-2	0.104
	2	0.208E-6	0.229E-3	0.716E-1	0.428E-5	0.334E-2	0.101
10	1				0.418E-5	0.330E-2	0.163
	2				0.428E-5	0.334E-2	0.168
13	1	0.341E-6	0.424E-3	0.203	0.418E-5	0.330E-2	0.226
	2	0.351E-6	0.447E-3	0.200	0.428E-5	0.334E-2	0.220

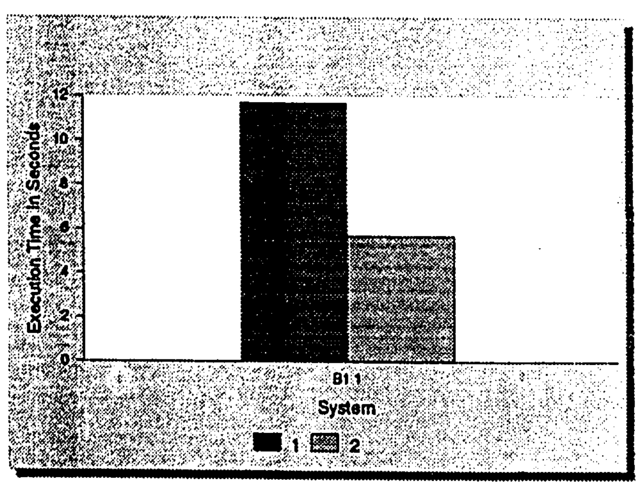

Figure 6.8: Comparison of execution time of two systems for case-6

6.5 Adequacy Assessment of Study System-C

6.5.1 Case-7: Reference Case

The adequacy analysis is conducted to single IEEE RTS system in the preceding sections. In this section, in order to show the applicability of equivalent technique to a large system sizes, the dimension of original RTS system is duplicated. Each individual RTS system is identical, and is linked by three lines as shown in the previous chapter (Study system-C chapter 6) . The area of interest is a full RTS system. Several sensitivity analyses are conducted to the new system. this case is also termed as case-7

The total installed capacity, peak load demand, number of buses and lines for IEEE RTS (replication) system is shown in Table 6.22. This is a reference case for system C when all transmission facilities are assumed to be available.

Table 6.22: System configuration for case-7

System	No. of buses	No. of Lines	Total gen. (MW)	Total Load (MW)
Original	48	79	6810.0	5700.0
Equivalent	26	37	6810.0	5700.0

The reliability evaluation is conducted on the system mentioned above. The results of original system and equivalent system are tabulated in the following tables 6.23, 6.24 and6.25.

Table 6.23: Expected load curtailed for Case-7

Expected Load Curtailed					
Cause	System	Amount (MW)	Energy	Duration	Frequency
Busbar Isolation	1	0.434	2.79	0.021	0.003
	2	0.220	1.43	0.011	0.002
Voltage Violation	1	5.961	62.961	1.523	0.153
	2	0.962	8.20	0.183	0.021
MVAR Violation	1	0.026	0.15	0.002	0.00
	2	0.002	0.01	0.001	0.00

The busbar reliability indices are evaluated and are given in the following table.

Table 6.24: load point indices for outage of case-7

Busbar No.	System	Busbar Isololation	
		Prob.	Energy
4	1	0.174E-6	0.112
	2	0.178E-6	0.115
5	1	0.139E-6	0.861E-1
	2	0.142E-6	0.883E-1
6	1	0.686E-6	0.815
	2	0.693E-6	0.835
14	1	0.222E-6	0.376
	2	0.227E-6	0.385

The maximum load curtailed is 88.23 MW to relieve the MVAR violation with probability of 3E-8, when LI19 and LI10 are out, during the adequacy evaluation of original system and these values are observed to be the same for equivalent system.

The following figure 6.9 gives the information of the execution time of both systems while the figure 6.10 gives information about the number of states of both

Table 6.25: Busbar reliability Indices for case-7

Busbar No.	System	Voltage Violation Prob.	Voltage Violation Freq.	Voltage Violation Energy	MVAR violation Prob	MVAR violation Freq.	MVAR violation Energy
3	1	0.143E-6	0.237E-3	0.811E-1			
	2	0.140E-6	0.235E-3	0.808E-1			
4	1	0.414E-7	0.582E-4	0.130E-2			
	2	0.410E-7	0.579E-4	0.128E-2			
6	1	0.735E-4	0.583E-1	0.282E+2			
	2	0.568E-4	0.580E-1	0.954E+1			
8	1	0.463E-7	0.730E-4	0.118E-1			
	2	0.135E-7	0.239E-4	0.114E-1			
9	1				0.312E-6	0.493E-3	0.809E-2
	2				0.320E-6	0.460E-3	0.800E-2
10	1				0.312E-6	0.493E-3	0.937E-2
	2				0.298E-6	0.490E-3	0.579E-2
13	1				0.312E-6	0.493E-3	0.573E-3
	2				0.345E-6	0.483E-3	0.569E-3

systems.

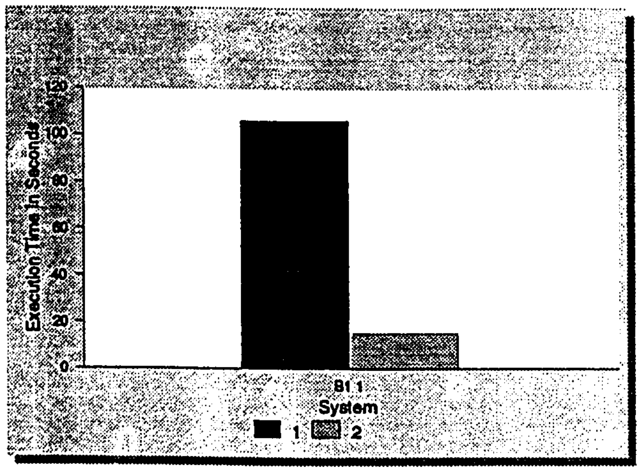

Figure 6.9: Comparison of execution time for both systems: Case-7.

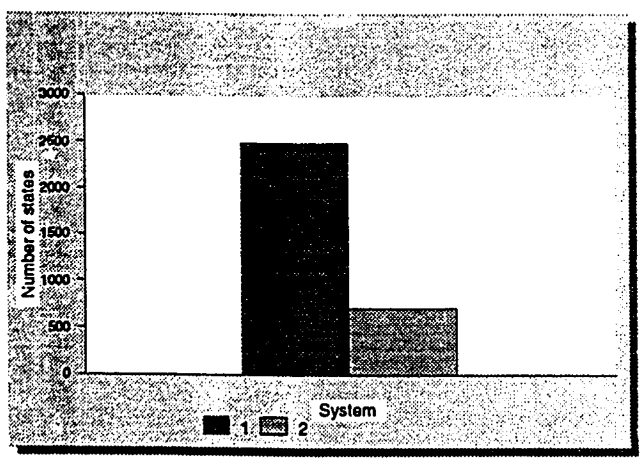

Figure 6.10: Comparison of the number of states of both systems for case-7.

6.5.2 Case-8: Outage of Line no. 28

Sensitivity analysis is conducted by taking line no. 28 out physically from the system (study system C). The results are shown in form of tables when adequacy analysis is conducted for both systems. The Table 6.26 shows the load curtailed for corrective measures, required for different problems in the network. The system 1 shows the load curtailed for full system and the system 2 represents equivalent system which consists of interested area only. Table 6.26 gives information about load curtailed in the area of interest and the rest of the area.

Table 6.26: Expected load curtailed for line no. 28 is out : Case-8

Expected Load Curtailed					
Cause	System	Amount (MW)	Energy	Duration	Frequency
Busbar Isolation	1	0.583	3.60	0.025	0.004
	2	0.372	2.26	0.014	0.002
Voltage Violation	1	8.283	77.25	1.755	0.183
	2	5.942	66.35	1.06	0.141
MVAR Violation	1	0.026	0.14	0.002	0.00
	2	0.021	0.10	0.00	0.00

Table 6.27 gives the information about the load point indices in the area of interest. The system 1 represents the original system and system 2 represents the equivalent system.

The maximum energy curtailed per state is observed to be 44.62 MW with the probability of 2.036E-5 during the adequacy analysis of original system, this amount

Table 6.27: Load point indices for outage for case-8

Busbar No.	System	Busbar Isolation.	
		Prob.	Energy
4	1	0.174E-6	0.112
	2	0.178E-6	0.115
5	1	0.139E-6	0.861E-1
	2	0.142E-6	0.883E-1
6	1	0.686E-6	0.815
	2	0.703E-6	0.813
14	1	0.222E-6	0.376
	2	0.228E-6	0.385
19	1	0.389E-6	0.616
	2	0.399E-6	0.631
20	1	0.173E-6	0.194
	2	0.177E-6	0.198

of load curtailed is observed when the line no. 10 is out. The corresponding value of maximum load curtailed in equivalent system is observed to be 44.68 MW with probability of 4.0E-5 when line 10 is out during the adequacy analysis.

figure 6.11 gives information about execution time of both systems when line no. 28 is taken out and reliability assessment is evaluated for both systems.

Table 6.28: Busbar reliability Indices for line 28 out of Case-8

Busbar Reliability Indices							
Busbar No.	System	Voltage Violation			MVAR violation		
		Prob.	Freq.	Energy	Prob	Freq.	Energy
3	1	0.267E-4	0.357E-1	0.151E+2	0.668E-7	0.104E-3	0.172E-2
	2	0.260E-4	0.350E-1	0.148E+2	0.660E-7	0.100E-3	0.170E-2
4	1	0.414E-7	0.582E-4	0.150E-2			
	2	0.271E-7	0.498E-4	0.146E-2			
6	1	0.753E-4	0.583E-1	0.286E+2			
	2	0.659E-4	0.580E-1	0.275E+2			
8	1	0.561E-7	0.942E-4	0.129E-1			
	2	0.389E-7	0.876E-4	0.120E-1			
9	1	0.444E-7	0.588E-4	0.231E-1	0.668E-7	0.104E-3	.502E-2
	2	0.287E-7	0.488E-4	0.230E-1	0.568E-7	0.100E-3	0.509E-2
10	1				0.668E-7	0.104E-3	0.268E-2
	2				0.568E-7	0.100E-3	0.260E-2
14	1				0.668E-7	0.104E-3	0.557E-2
	2				0.671E-7	0.905E-3	0.549E-2
15	1				0.668E-7	0.104E-3	0.504E-2
	2				0.610E-7	0.100E-3	0.500E-2
16	1				0.668E-7	0.104E-3	0.228E-2
	2				0.671E-7	0.100E-3	0.242E-2

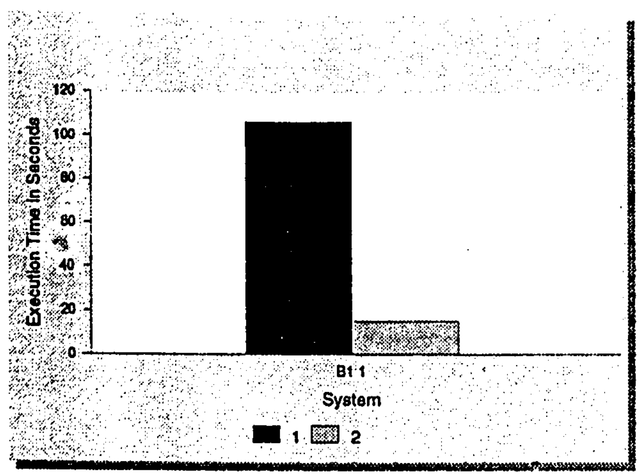

Figure 6.11: Comparison of execution time of both systems: case-8.

6.5.3 Case-9: Outage of Line no. 34

For this study case, line 34 is taken out (from study system C chapter 6) and adequacy analysis is carried out. The results obtained are given in tables 6.29, 6.30 and 6.31 Table 6.29 gives information about load curtailed which occur for the corrective action for different problems in the system. The system 1 represent the original system and the system 2 represents the equivalent system. System 1 is original system and system 2 represents the equivalent.

Table 6.29: Expected load curtailed for case-9

Expected Load Curtailed					
Cause	System	Amount (MW)	Energy	Duration	Frequency
Busbar Isolation	1	0.434	2.79	0.021	0.003
	2	0.220	1.43	0.011	0.002
Voltage Violation	1	5.95	62.22	1.523	0.513
	2	3.925	45.87	1.043	0.354
MVAR Violation	1	0.029	0.17	0.002	0.00
	2	0.001	0.11	0.001	0.00

The maximum energy or load curtailed per state is observed to be 44.65 MW with probability of 6.97E-5 when adequacy program is considering lines 19 & 20 out for original system and for equivalent system, maximum load curtailed per state is observed to be 44.65 MW with probability of 2.036E-5 when reliability program is considering the lines 19 & 20 out. The following tables gives the information about the busbar indices in the area of interest for the original system and the equivalent system.

Table 6.30: load point indices for outage of case-9

Busbar No.	System	Busbar Isol.		Line Over.	
		Prob.	Energy	Prob	Freq.
4	1	0.174E-6	0.112		
	2	0.178E-6	0.115		
5	1	0.139E-6	0.861E-1		
	2	0.142E-6	0.883E-1		
6	1	0.686E-6	0.851		
	2	0.703E-6	0.836		
14	1	0.222E-6	0.376		
	2	0.228E-6	0.385		

figure 6.12 gives the information regarding the execution time of both the system when reliability was calculated for line 34 out.

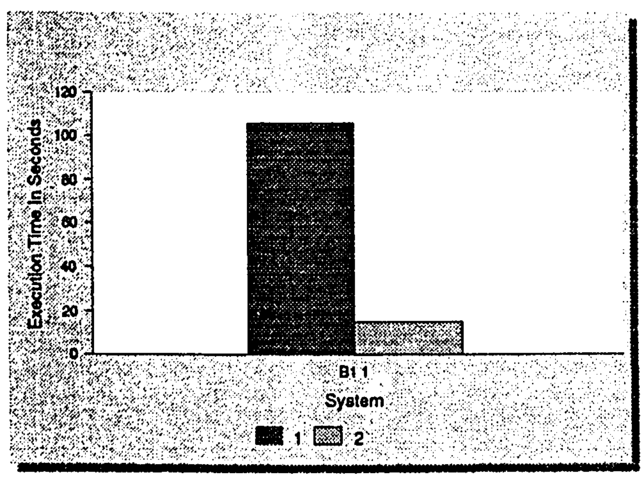

Figure 6.12: Comparison of execution time for both systems for Case-9.

Table 6.31: Busbar reliability Indices for case-9

Busbar Reliability Indices							
Busbar No.	System	Voltage Violation			MVAR violation		
		Prob.	Freq.	Energy	Prob	Freq.	Energy
1	1				0.920E-7	0.121E-3	0.299E-3
	2				0.178E-7	0.171E-3	0.290E-3
3	1	0.133E-6	0.216E-3	0.723E-1	0.920E-7	0.121E-3	0.225E-2
	2	0.120E-6	0.200E-3	0.720E-1	0.918E-7	0.190E-3	0.220E-2
4	1	0.414E-7	0.582E-4	0.129E-2			
	2	0.356E-7	0.653E-4	0.126E-2			
6	1	0.735E-4	0.583E-4	0.286E+2			
	2	0.710E-4	0.573E-1	0.260E+2			
8	1	0.463E-7	0.730E-4	0.118E-1			
	2	0.368E-7	0.700E-4	0.110E-1			
9	1				0.404E-6	0.614E-3	0.103E-1
	2				0.593E-6	0.600E-3	.100E-1
10	1				0.312E-6	0.493E-3	0.935E-2
	2				0.314E-6	0.400E-3	0.883E-2
13	1				0.3121E-6	0.493E-3	0.638E-1
	2				0.290E-6	0.400E-3	0.620E-1
14	1				0.920E-7	0.121E-3	0.242E-1
	2				0.493E-7	0.825E-4	0.230E-1
15	1				0.920E-6	0.121E-3	0.396E-1
	2				0.178E-7	0.119E-3	0.300E-1
16	1				0.920E-6	0.121E-3	0.285E-3
	2				0.178E-7	0.119E-3	0.258E-3
19	1				0.920E-7	0.121E-3	0.102E-2
	2				0.920E-7	0.119	0.100E-2

6.5.4 Case-10: Outage of Line no. 31

Line 31 is a double circuit line. The outage of both lines are considered at a time because it is a common mode event. Sensitivity analysis is conducted for the adequacy analysis of both systems. The results of the adequacy indices are tabulated below. Table 6.32 gives the amount of the load curtailed for the original system and the equivalent system. System 1 is original system and system 2 represents the equivalent.

Table 6.32: Expected load curtailed for case-10

Expected Load Curtailed					
Cause	System	Amount (MW)	Energy	Duration	Frequency
Busbar Isolation	1	0.434	2.79	0.021	0.003
	2	0.220	1.43	0.011	0.002
Voltage Violation	1	5.954	62.26	1.523	0.153
	2	4.653	60.654	1.509	0.150
MVAR Violation	1	0.027	0.15	0.002	0.00
	2	0.020	0.10	0.002	0.00

Table 6.33: load point indices for Case-10

Busbar No.	System	Insuff. Gen.		Busbar Isol.		Line Over.	
		Prob.	Energy.	Prob.	Energy	Prob	Freq.
4	1			0.174E-6	0.112		
	2	0.178E-6	0.115				
5	1			0.139E-6	0.862		
	2			0.142E-6	0.883		
6	1			0.686E-6	0.815		
	2			0.704E-6	0.836		
14	1			0.222E-6	0.376		
	2			0.228E-6	0.386		

Table 6.34: Busbar reliability Indices for case-10

Busbar Reliability Indices							
Busbar No.	System	Voltage Violation			MVAR violation		
		Prob.	Freq.	Energy	Prob	Freq.	Energy
3	1	0.133E-6	0.216E-3	0.753E-1			
	2	0.100E-6	0.200E-3	0.734E-1			
4	1	0.414E-7	0.582E-4	0.145E-2			
	2	0.400E-7	0.580E-4	0.140E-2			
6	1	0.735E-4	0.583E-1	0.286			
	2	0.700E-4	0.578E-1	0.280			
8	1	0.464E-7	0.730E-4	0.118E-1			
	2	0.460E-7	0.700E-4	0.116E-1			
9	1				0.312E-6	0.493E-3	0.801E-2
	2				0.310E-6	0.480E-3	0.780E-2
10	1				0.312E-6	0.493E-3	0.939E-2
	2				0.310E-6	0.480E-3	0.900E-2
13	1				0.312E-6	0.493E-3	0.546E-3
	2				0.310E-6	0.480E-3	0.540E-3
18	1	0.141E-7	0.297E-4	0.171E-1			
	2	0.120E-7	0.289E-4	0.170E-1			

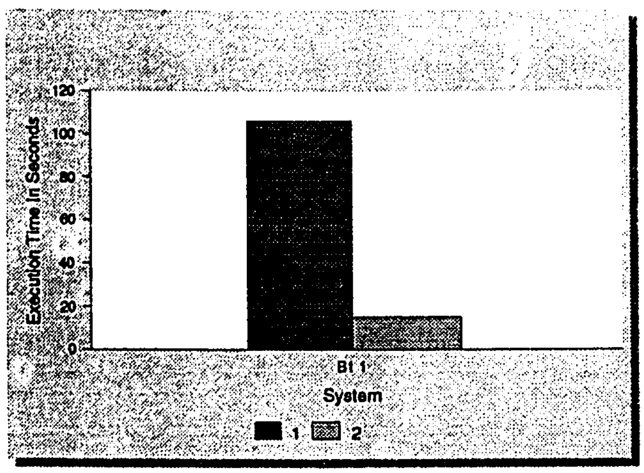

Figure 6.13: Comparison of execution time of both systems for case-10.

Chapter 7

Conclusions And Discussion of Results

In adequacy analysis of a composite power system, if quality of power supply is also of concern then AC load flow analysis is conducted for the solution of the power system. The concept of adequacy equivalents is used to overcome the problem of large execution time required for the evaluation of adequacy of a composite power system. Equivalencing approaches are employed either for the physical reduction of power system or reduction in state space of power system (as described in chapter 2). A new equivalencing technique is presented in this thesis and its validitation is done by an exhaustive study with respect to load flow analysis (chapter 5) and with respect to adequacy analysis (chapter 6). Two types of equivalencing models are formulated for a part of a power system. The first model, 'Deterministic model' represents the external area, by equivalent generation, transmission and load at the boundary buses without considering the stochastic behavior of transmission facilities in external area. The second model, 'Probabilistic model' takes the stochastic behavior of the transmission lines into consideration while evaluating the equivalent models for external area. These equivalent models can be utilized to assess the adequacy of a small area in a composite power system. The proposed equivalent can also model the variation of load and generation in external area, utilizing the concept of distribution factors.

The validation of the equivalent model is done by comparing results of load flow (FDLF) analysis i.e. the original system and the equivalent system. Results obtained from load flow analysis reveal satisfactory performance and prove validity of the equivalencing algorithm developed in chapter 3. However, mismatches may appear for some cases at boundary buses. These mismatches are a manifestation of the fact that power interchanges between internal area and external area, at boundary buses, are not in complete agreement. In order to reduce boundary mismatches, a buffer zone may be needed between area of interest and boundary buses.

The adequacy analysis conducted in chapter 6 give confidence in the new equivalencing technique. The number of states of the equivalent system is reduced significantly with respect to its original system. Consequently execution time of the equivalent system is also reduced significantly.

Chapter 8

Future Work And Recommendations

Before this research there was no equivalent ever mentioned in the literature which could utilize in AC load flow method to check the quality of power supply by evaluating the adequacy indices, perhaps the are adequacy equivalent available for the adequacy analysis of a composite power system by utilizing the DC load flow method. But this type of analysis could not provide any information about the quality of power supply. An AC load flow solution is of iterative nature which is more time consuming and convergence of the solution depends upon the operating points and the configuration of the network. To decrease the time required for the adequacy analysis more investigation is needed in developing the following measures:

- A fast and efficient load shedding routine for the swift corrective action to alleviate the system problem.
- A fast and efficient generation and redispatch routine for the relief measures to the system problem.

The above improvements will help significantly to reduce the time required for AC adequacy analysis. The number of states in the proposed equivalent could also be reduced by improving the model of the external generation. This could be achieved by reducing the number of states associated with the external generation.

The adequacy analysis should also be realized by incorporating the weather model in the study. This will take into account the stochastic behavior of the weather while evaluating the adequacy of the system. Three widely recommended models , fair, bad and stormy model could be utilized to incorporate weather effect on the power system. Load shedding routine is applied when breach in quality is detected for any state of the system. It is possible that system problem may be alleviated by curtailing the load. Different power utilities have different criteria for load shedding. The execution time can be reduced, needed for adequacy evaluation of power system by employing a fast load shedding routine.

Appendix A

IEEE RTS 24 Bus System Data

A.1 Single Line Diagram

The single line diagram of the IEEE RTS system is shown in the Fig. A.1 This was established by IEEE task force in 1979 [3]. It has 10 generators (PV) buses 10 load (PQ) buses, 34 transmission lines and 5 transformers. The total load is 2850 MW and the total generation is 3405 MW. The full information of the system could be obtained from ref. [3]. IEEE- RTS system data are shown in tables A.1 - A.5.

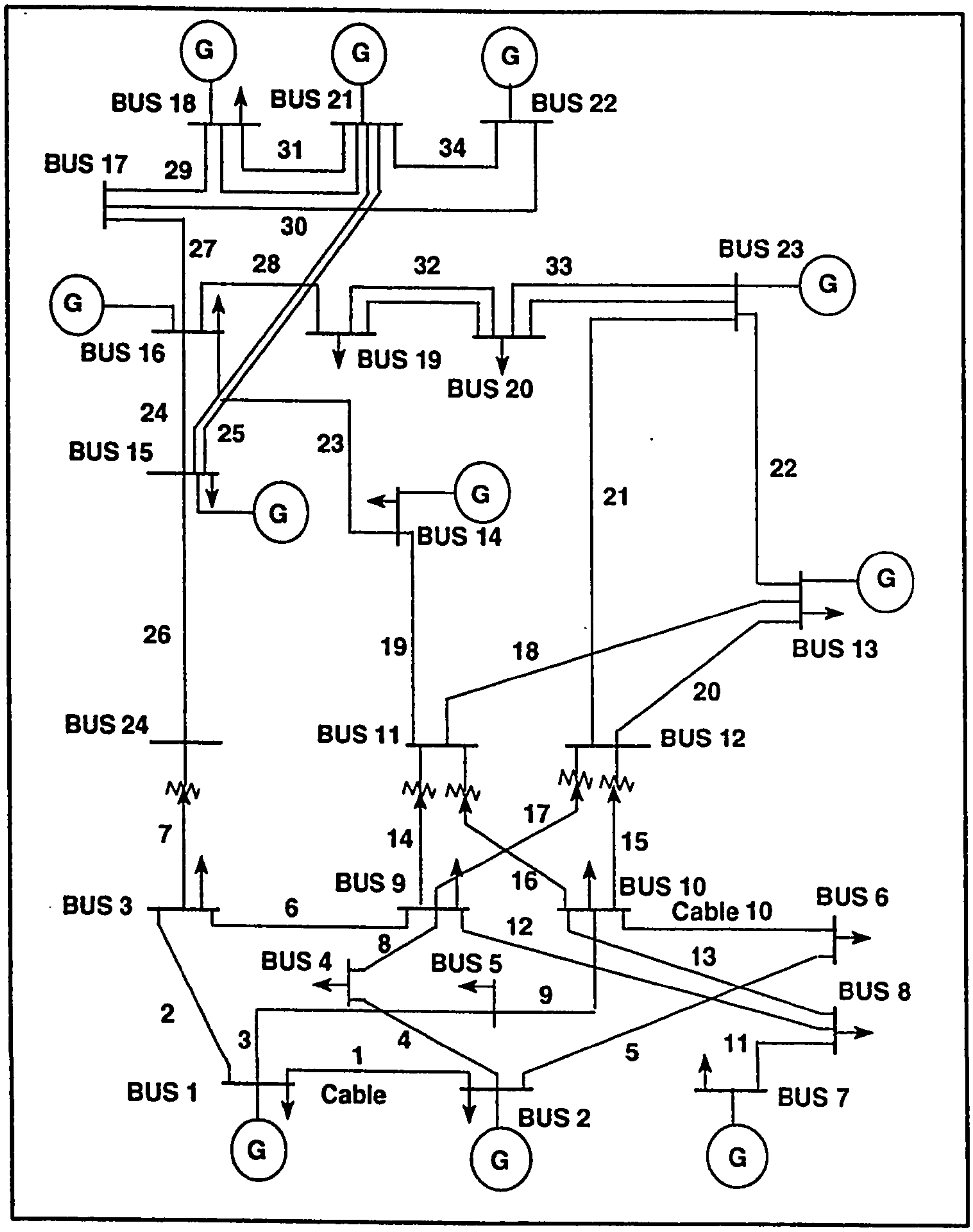

Figure A.1: IEEE-RTS 24 Bus System [3]

A.2 Bus Data

The IEEE RTS system consists of 24 buses. Three of them are net generating busbars, nine are net load busbars, eight buses are generating and the load busbars while the remaining four buses are the switching busbars. Bus no. 23 is the slack bus and the bus no. 13 is the optional slack bus. Table A.1 shows the busbar data

Table A.1: IEEE RTS Busbar Data

Busbar name	*Activepower generation*	*Active load*	*ReactiveLoad*	*Curtailable load*
01	152.00	108.00	22.0	80.00
02	152.00	97.00	20.0	80.00
03	0.00	180.00	37.0	80.00
04	0.00	74.00	15.0	80.00
05	0.00	71.00	14.0	80.00
06	0.00	136.00	28.0	80.00
07	150.00	125.00	25.0	80.00
08	0.00	171.00	35.0	80.00
09	0.00	175.00	36.0	80.00
10	0.00	195.00	40.0	80.00
11	0.00	0.00	0.0	80.00
12	0.00	0.00	0.0	80.00
13	400.00	265.00	54.0	80.00
14	0.00	194.00	39.0	80.00
15	155.00	317.00	64.0	80.00
16	155.00	100.00	20.0	80.00
17	0.00	0.00	0.0	80.00
18	400.00	333.00	68.0	80.00
19	0.00	181.00	37.4	80.00
20	0.00	128.00	26.0	80.00
21	400.00	0.00	0.0	80.00
22	300.00	0.00	0.0	80.00
23	0.00	0.00	0.0	80.00
24	0.00	0.00	0.0	80.00

A.3 Generating Data

The total installed capacity of IEEE RTS system is 3405.00 MW. This amount of generation is supplied by total of 14 generating groups. The available generation is increased by 0.1 MW by the synchronous condenser connected to busbar 14. Table A.2 shows the generation data. MTTF is mean time to failure and MTTR is mean time to repair of generating units.

Table A.2: IEEE RTS generating data

Group	Ident. name	No. of units	Max. power	Min. power	MTTF Hours	MTTR Hours	Bus no.
1	S8G2	2	20.00	16.00	450.0	50.00	01
2	S9G2	2	20.00	16.00	450.0	50.00	02
3	S4G1	3	197.00	68.95	950.0	50.00	13
4	S1G1	1	400.00	100.00	1100.0	150.00	18
5	S2G1	1	400.00	100.00	1100.0	150.00	21
6	S7G1	3	100.00	25.00	1200.0	50.00	07
7	S5G2	5	12.00	2.40	2940.0	60.00	15
8	S3G1	1	350.00	140.00	1150.0	100.00	23
9	S3G2	2	155.00	54.25	960.0	40.00	23
10	S0G1	6	50.00	5.00	1980.0	20.00	22
11	S5G1	1	155.00	54.25	960.0	40.00	15
12	S6G1	1	155.00	54.25	960.0	40.00	16
13	S6G1	2	76.00	15.20	1960.0	40.00	01
14	S9G1	2	76.00	15.20	1960.0	40.00	02
15	SSR1	1	0.01	0.00	9999.0	.01	14

A.4 Transmission System

The total number of transmission lines are 38 in IEEE RTS system. There are 31 overhead lines, 2 are under ground cables and 5 are transformers. There are 4 groups of double circuits so we could make 34 group of lines. S.Bus is sending bus and R.Bus is the receiving bus of the line. The transmission lines data are presented in Table A.3

Table A.3: Transmission line of IEEE RTS system

Line no.	Name	*S.* Bus	*R.* Bus	*R* (p.u.)	*X* (p.u.)	*B* (*p.u.*)	*Rating* (MVA)	*Out.* rate	*Out. dur.*	*no.of lines*
1	LI01	01	02	0.0026	0.0139	0.4611	175.0	0.24	16.00	1
2	LI02	01	03	0.0546	0.2112	0.0572	175.0	0.51	10.00	1
3	LI03	01	05	0.0218	0.0845	0.0029	175.0	0.33	10.00	1
4	LI04	02	4	0.0326	0.1267	0.0343	175.0	0.39	10.00	1
5	LI05	02	6	0.0497	0.1920	0.0520	175.0	0.48	10.00	1
6	LI06	03	9	0.0308	0.1190	0.0.0322	175.0	0.38	10.00	1
7	LI07	24	3	0.0023	0.0839	0.0000	400.0	0.02	768.0	1
8	LI08	04	9	0.0268	0.1037	0.0281	175.0	0.36	10.00	1
9	LI09	05	10	0.0228	0.0883	0.0239	175.0	0.34	10.00	1
10	LI10	06	10	0.0139	0.0605	2.4590	175.0	0.33	35.00	1
11	LI11	07	8	0.0159	0.0614	0.0166	175.0	0.30	10.00	1
12	LI12	08	9	0.0427	0.1651	0.0447	175.0	0.44	10.00	1
13	LI13	08	10	0.0427	0.1651	0.0447	175.0	0.44	10.00	1
14	LI14	11	09	0.0023	0.0839	0.0000	400.0	0.02	768.0	1
15	LI15	12	10	0.0023	0.0839	0.0000	400.0	0.02	768.0	1
16	LI16	11	10	0.0023	0.0839	0.0000	400.0	0.02	768.0	1
17	LI17	09	12	0.0023	0.0839	0.0000	400.0	0.02	768.0	1
18	LI18	11	13	0.0061	0.0476	0.0999	500.0	0.40	11.00	1
19	LI19	11	14	0.0054	0.0418	0.0879	500.0	0.39	11.00	1
20	LI20	12	13	0.0061	0.0476	0.0999	500.0	0.40	11.00	1
21	LI21	12	23	0.0124	0.0966	0.2030	500.0	0.52	11.00	1
22	LI22	13	23	0.0111	0.0865	0.1818	500.0	0.49	11.00	1
23	LI23	14	16	0.0050	0.0389	0.0818	500.0	0.38	11.00	1
24	LI24	15	16	0.0022	0.0173	0.0364	500.0	0.33	11.00	1
25	LI25	15	21	0.0063	0.0490	0.1030	500.0	0.41	11.00	2
26	LI26	15	24	0.0067	0.0515	0.1090	500.0	0.41	11.00	1
27	LI27	16	17	0.0033	0.0259	0.0545	500.0	0.35	11.00	1
28	LI28	16	19	0.0030	0.0231	0.0485	500.0	0.34	11.00	1
29	LI29	17	18	0.0018	0.0144	0.0303	500.0	0.32	11.00	1
30	LI30	17	22	0.0135	0.1053	0.2212	500.0	0.54	11.00	1
31	LI31	18	21	0.0033	0.0259	0.0545	500.0	0.35	11.00	2
32	LI32	19	20	0.0051	0.0396	0.0838	500.0	0.38	11.00	2
33	LI33	20	23	0.0028	0.0216	0.0455	500.0	0.34	11.00	2
34	LI34	21	22	0.0087	0.0678	0.1424	500.0	0.45	11.00	1

A.5 System Replication

For the replication of the IEEE RTS system of case 3 and case-4 in chapter 6 and chapter 7 the following tie lines data was used. The both the RTS systems are identical.

Table A.4: IEEE RTS transmission linked data

Line no.	*Name*	*S. Bus*	*R. Bus*	*R* (p.u.)	*X* (p.u.)	*B* (p.u.)	*Rating* (MVAR)	*Out.* rate	*Out.* dur.	*No.of* lines
35	LI35	23	40	0.0032	0.0489	0.0455	500.0	0.240	16.1	2
36	LI36	13	39	0.0050	0.04889	0.0455	500.0	0.240	16.1	1

Table A.5: IEEE RTS transmission linked data(two replicant case-4)

Line no.	*Name*	*S. Bus*	*R. Bus*	*R* (p.u.)	*X* (p.u.)	*B* (p.u.)	*Rating* (MVAR)	*Out.* rate	*Out.* dur.	*No.of* lines
35	LI35	1	25	0.0063	0.0868	0.1424	500.0	0.240	16.1	1
36	LI36	2	26	0.0063	0.0868	0.0545	500.0	0.240	16.1	1
37	LI37	7	31	0.0050	0.0389	0.0545	500.0	0.240	16.1	1

Appendix B

Software Implementation

A computer program for evaluating the equivalent model for the external system is developed in this thesis. The main feature of this program is to calculate the probabilistic equivalent models of the generation, load and transmission components, in the external system. These models will represent the facilities in the external system on the boundary busbars. The function of the program could be analysed from the flow chart B.1. The external system can either be modeled by deterministic or by probabilistic model.

The flow chart shown in Fig. B.2 gives the algorithm for the eavaluation of the Adequacy for a composite power system.

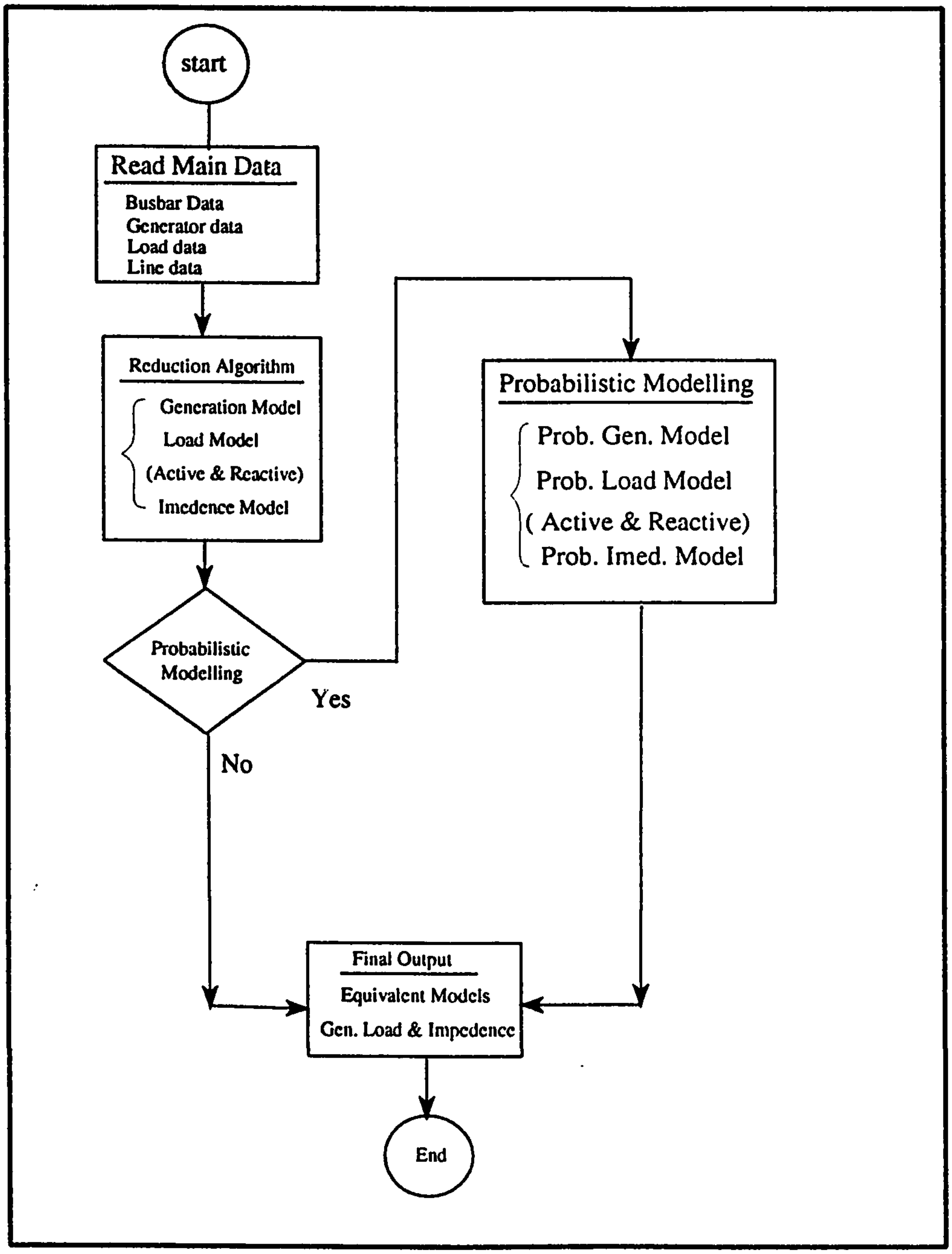

Figure B.1: Flow Chart of The Equivalencing Procedure.

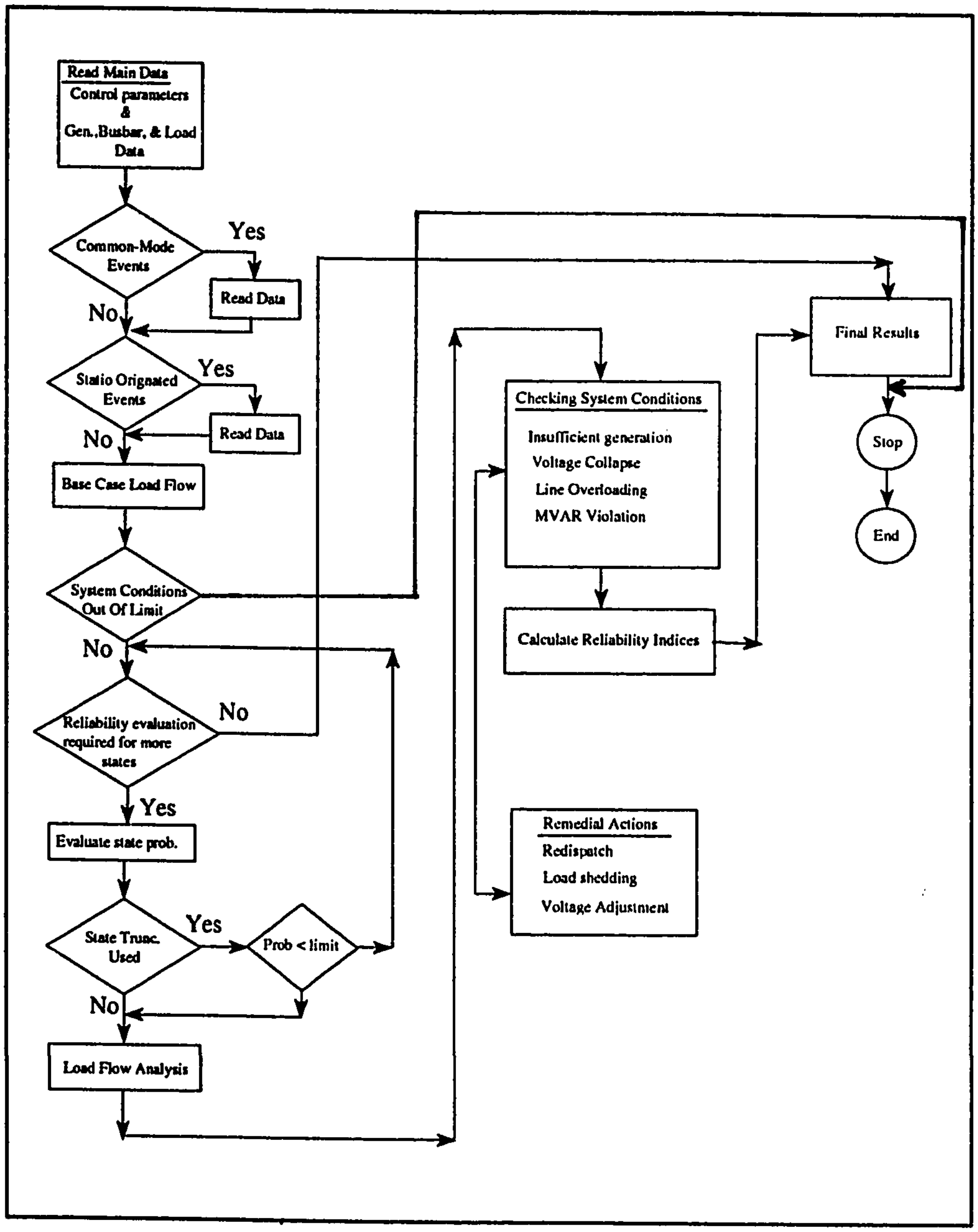

Figure B.2: Flow Chart of Adequacy Evaluation Algorithm [4].

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